FISCAL YEAR 1988 DEPARTMENT OF ENERGY AUTHORIZATION
(Transportation Programs)

HEARING

BEFORE THE

SUBCOMMITTEE ON TRANSPORTATION, AVIATION AND MATERIALS

OF THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY HOUSE OF REPRESENTATIVES

ONE HUNDREDTH CONGRESS

FIRST SESSION

MARCH 3, 1987

[No. 10]

Printed for the use of the
Committee on Science, Space, and Technology

U.S. GOVERNMENT PRINTING OFFICE

73-573 WASHINGTON : 1987

For sale by the Superintendent of Documents, Congressional Sales Office
U.S. Government Printing Office, Washington, DC 20402

H701-56

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*Ranking Republican Member.
**Resigned February 19, 1987 (H. Res. 89).
***Elected March 30, 1987 (H. Res. 133).

CONTENTS

WITNESSES

March 3, 1987:

Page

Miss Donna R. Fitzpatrick, Assistant Secretary for Conservation and Renewable Energy, U.S. Department of Energy, Washington, DC, accompanied by Dr. Berg and Mr. Streb 3

Harold E. Helms, chief engineer, Vehicular Turbines, Allison Gas Turbine Division, Power Products Group, General Motors Corp.; Edwin Strain, manager of Government Programs, Power Systems, Garrett Turbine Engine Co., the Garrett Corp., accompanied by Dan Kreiner, project manager for AGT and ATTAP Programs; Dr. William F. Powers, director, Power Train and Systems Research Laboratory, Ford Motor Co.; and Noel Nightingale, assistant general manager, Stirling Engine Systems Division, Mechanical Technology, Inc., accompanied by Greg Gutgsell, John Deere Co 120

Dr. Vincent Halsall, vice president, Advanced Battery Unit, Johnson Controls, Inc., Milwaukee, WI, accompanied by William Gentry and James Strang, director of engineering, Environmental and Heat Transfer Systems, Enterprise, Airesearch Manufacturing Co., Torrance, CA.... 188

APPENDICES

I. Corrections and clarifications to the record 243

II. Statement of Deborah Lynn Bleviss, Executive Director, International Institute for Energy Conservation 244

FISCAL YEAR 1988 DEPARTMENT OF ENERGY AUTHORIZATION

(Transportation Programs)

TUESDAY, MARCH 3, 1987

HOUSE OF REPRESENTATIVES, COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY, SUBCOMMITTEE ON TRANSPORTATION, AVIATION AND MATERIALS

Washington, DC.

The subcommittee met, pursuant to notice, at 2:15 p.m., in room 2325, Rayburn House Office Building, Hon. Dave McCurdy (chairman of the subcommittee) presiding.

Staff present: Curt Stanford, technical consultant; James Green, minority technical consultant; and Harriet Smith.

Mr. MCCURDY. Good afternoon.

Miss. FITZPATRICK. Good afternoon, Mr. Chairman.

Mr. MCCURDY. We apologize for running a little bit late. We were out looking at the new car, the new technology out in the horseshoe there, and fortunately they wouldn't let us drive it, or we wouldn't be here yet.

Today the Subcommittee on Transportation, Aviation and Materials will consider the Department of Energy's FY '88 budget request for transportation research and development. These programs were largely mandated by two bills which originated in the Science and Technology Committee, the Automotive Transport Research and Development Act and the Electric Vehicle Research, Development, and Demonstration Act. So we are particularly interested in reviewing their progress.

The development of advanced automotive technology and the high-temperature materials on which many of the advanced engines rely is critical not only to the energy independence of the United States, but also to the future competitiveness of the U.S. industry. And that's not the last time you'll here competitiveness mentioned in this Congress, I'm sure.

Clearly, we must consider the importance of these research and development programs as a key component of our long-term security.

The budget request for fiscal year 1988 is $22.4 million, less than half of what was appropriated for fiscal year 1987. I might state here that in the Armed Services Committee, we generally round off at larger numbers than what this budget request is for, and some people might wonder why we spend as much time on this amount of money. But quite frankly, we are extremely concerned that this

receive a priority, and that while many of the automotive programs are moving successfully toward achieving the goals set out in the enacting legislation, we still have a long way to go, particularly in establishing the key ceramic and advanced materials technology base necessary for their success.

Likewise, advancements in battery and electric vehicle technology still have not reached their full potential. While we must remain aware of current budget limitations, it is the responsibility of Congress to review the priorities proposed by the budget request to determine if they are, indeed, in the best interest of the nation.

I look forward to a very informative and productive hearing, and we welcome the expert witnesses who have agreed to assist the subcommittee today.

At this point, I would recognize Mr. Lewis, the ranking Republican member of the committee.

Mr. LEWIS. Thank you, Mr. Chairman.

I strongly support the objective of the Department of Energy's transportation program, which is to improve energy efficiency and develop technologies that would enhance non-oil use. For the moment, we do not have an oil shortage, but we do have a serious trade imbalance problem. At the heart of the problem is the importation of vehicles, many of which are more fuel-efficient than those made in the United States. Therefore, it is important that we support the appropriate research efforts that will assist U.S. companies in getting the technology edge in fuel efficiency.

And I am concerned, when I did see the DOE Fiscal '88 budget of $22.4 million. This is a sizeable decrease, and I am interested in finding out if these budget cuts are reasonable and prudent or too severe and unwise.

So I look forward to hearing these witnesses today, Mr. Chairman, addressing these concerns.

Thank you.

Mr. MCCURDY. Thank you, Mr. Lewis.

At this point, I would ask unanimous consent to allow video and audio coverage of the hearing proceedings today. Without objection.

Mr. Walker, any comments?

If not, we will begin. Thank you. He did indicate earlier that with the prototype outside, we'd have to change the speed limit, on which he and I are wholeheartedly in agreement, and with that bit of advertising——

Mr. WALKER. We need to figure out a way to work that into this budget request.

Mr. MCCURDY. That's right. [Laughter.]

Maybe we could tie it to that. It is currently in conference, and we have been stressing to our relevant conferees that it's an important item, and we'd like to see it resolved.

Our first witness, of course, is Miss Donna Fitzpatrick, Assistant Secretary for Conservation and Renewable Energy, Department of Energy, and with her is Dr. Berg and Mr. Streb.

With that introduction, please proceed.

STATEMENT OF MISS DONNA R. FITZPATRICK, ASSISTANT SECRETARY FOR CONSERVATION AND RENEWABLE ENERGY, U.S. DEPARTMENT OF ENERGY, WASHINGTON, DC, ACCOMPANIED BY DR. BERG AND MR. STREB

Miss FITZPATRICK. Thank you, Mr. Chairman.

I have a full statement which I would like to submit for the record, if I may.

Mr. MCCURDY. It will be entered in its entirety, and we appreciate your summarizing.

Miss FITZPATRICK. I appreciate the opportunity to appear before the subcommittee today and provide information on our Fiscal Year 1988 request concerning the Department's energy conservation research and development programs in the transportation area.

The transportation sector of the United States' economy used 20.7 quads of energy in 1986, which was a little less of one-third—excuse me—it was about 27 percent of our total consumption. The vast majority of it was in the form of oil, representing about 10 million barrels per day. This is 63 percent of all the petroleum consumed in the United States.

The total petroleum consumption in the U.S. has fallen since 1973, but most of the decrease has been in the non-transportation areas, even though most transportation modes have experienced large increases in efficiency during the same period.

Other end-use sectors have been able to incorporate alternative fuels instead of petroleum; however, such a shift is not easily achieved in the transportation sector.

The goal of our transportation program is to improve energy efficiency and enhance the flexibility of fuel use options in transportation-related technologies. The research and development activities focus on selected high-risk ventures which are not likely to be pursued by the private sector alone. Most are carried out by private companies and institutions operating under cost-shared contracts or cooperative agreements with the Department. These activities complement industry efforts and do not displace them.

My written statement provides in greater detail the progress we have made in meeting the goals and objectives of the various programs and describes our operating plans for the current fiscal year.

The activities of the Department's transportation program cover a spectrum of projects structured to increase energy efficiency and reduce petroleum dependence. Although the program is focused on the transportation sector, the technologies under development for high-temperature materials, advanced propulsion systems, batteries, and alternative fuels utilization have a wide range of applications in addition to transportation.

All of this program is being carried out within the strict budget constraints which are required for deficit reduction.

That concludes my remarks, Mr. Chairman, and I thank you for the opportunity to appear today.

[The prepared statement of Miss Fitzpatrick follows:]

STATEMENT OF

DONNA R. FITZPATRICK

ASSISTANT SECRETARY

CONSERVATION AND RENEWABLE ENERGY

BEFORE THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

SUBCOMMITTEE ON TRANSPORTATION, AVIATION AND MATERIALS

U.S. HOUSE OF REPRESENTATIVES

MARCH 3, 1987

Mr. Chairman and Members of the Subcommittee, I appreciate the opportunity to appear before you today and provide information on the FY 1988 budget request concerning the Department's energy conservation research and development programs in the transportation area.

TRANSPORTATION RELATED GOALS

The transportation sector used 20.7 quads of energy in 1986, the vast majority of which was in the form of oil, representing 10 million barrels per day and 63 percent of all petroleum consumed in the United States each day. In fact, the transportation sector has used more petroleum than the U.S. has been able to produce in every year since 1976. In 1986, transportation used 7 percent more petroleum than the U.S. produced.

Total petroleum consumption in the U.S. has fallen since 1973, but most of the decrease has been in non-transportation uses, even though most transportation modes experienced large increases in fuel efficiency during this same period. For example, new car fuel economy grew from 14.2 mpg in 1973 to 27.9 mpg in 1986, a gain of 96 percent. The fuel economy of all cars on the road changed more slowly, but average fuel economy still rose from 13.1 mpg in 1973 to 18.4 mpg in 1986 (a gain of 40 percent). Even though automobile travel rose 26 percent during this time, overall automobile fuel use declined 6 percent.

Other end-use sectors have been able to substitute alternative fuels for petroleum; however, such a shift is not easily achieved in the transportation sector. The petroleum share of transportation energy use

rose slightly from 95.8 percent in 1973 to 97.3 percent in 1986.

The goal of the transportation conservation program is to improve energy efficiency and enhance the flexibility of fuel use options in transportation-related technologies. This goal is underscored by the fact that such technologies have potentially significant leverage on the U.S. and world oil situation. Reductions in U.S. transportation oil use can enhance energy security, reduce oil imports and related trade payments to foreign countries, and enhance economic growth.

Because of the transportation sector's important role in the economic health and vitality of the Nation, it is essential that the movement of people and goods be accomplished in as efficient a manner as economically practical and in concert with a strong set of domestic manufacturers and suppliers. The research supported by this program is aimed at assisting domestic firms with the needed technology options that will allow them to face an uncertain future with respect to energy mix and price and with respect to international competition. The research is aimed at far-term R&D that the industry will not perform on its own, usually R&D for which significant levels of risk exist. All government funds complement industry expenditures and do not displace them.

FY 1988 BUDGET

The FY 1988 budget request in the transportation area totals $22.4 million for operating expenses. This funding is required to continue a program of research and development based on specific objectives

generated in accordance with industry inputs. The objectives include efforts to: (a) develop scientific knowledge and proofs-of-concepts for advanced engine technologies that demonstrate at least 30 percent improvement in fuel economy over conventional current production heat engines under similar vehicle weight to horsepower conditions, capability to meet emissions, safety and noise standards, and competitive initial and life-cycle costs when in production; (b) overcome key technological barriers, particularly relating to energy storage, concerning private sector development of electric and hybrid vehicles; (c) establish a fundamental ceramic and advanced materials technology base to support the U.S. heat engine industry; and (d) encourage the development of alternative technologies by providing industry with fundamental scientific information on the properties and behavioral characteristics of alternative transportation fuels made from oil shale, coal, and biomass.

I would now like to describe our progress, our planned activities during FY 1987, and our request for FY 1988 for each of the sub-programs in the areas under your jurisdiction.

VEHICLE PROPULSION R&D

For the past several years, the focus of the Vehicle Propulsion R&D program has been on development of advanced automotive gas turbine and Stirling engines and heavy duty transport uncooled, minimum friction diesel engines with integrated waste heat recovery. These engine projects were formulated in response to the Automotive Propulsion Research and Development Act of 1978 (Title III of P.L. 95-238) with the

intent that high-risk engine design concepts and technology barriers would be sufficiently proven so that industry could proceed with commercialization.

The major projects under the Automotive Gas Turbine (AGT) Technology program have been two cost-shared, proof-of-concept engine development contracts. The two designs are: (1) a single-shaft configuration (AGT 101) being developed by the Garrett Corporation, and (2) a two-shaft concept (AGT 100) by Allison Gas Turbine Division of General Motors. Experimental versions of both engine designs have been fabricated and are available for tests and demonstrations. Development of high temperature structural ceramic components has been a major part of the program because high operating temperatures are necessary to achieve the efficiency goals of the AGT engines. Advanced ceramic components were integrated into the test engines and proof-of-concept was achieved in FY 1986 with a dynamometer performance characterization of the high temperature configurations, completing the major AGT development tasks.

A new program is being initiated in FY 1987 which focuses on ceramic component development for gas turbines. The new effort will utilize the component test rigs and engines fabricated during the AGT program to test and evaluate advanced ceramic components as they are developed. Both AGT contractors are being asked to submit proposals for cost-shared contracts to build advanced ceramic components and evaluate their performance in engine environments. Negotiations will be conducted with both teams and the ceramic suppliers they share to create a single cooperative effort. In FY 1988, $4 million is being requested to

continue ceramic component development and evaluation within this single cooperative effort.

The Automotive Stirling Engine (ASE) Technology program is centered on a proof-of-concept engine development contract awarded to an industry team led by Mechanical Technology Incorporated, with United Stirling AB & Company as the major subcontractor. During FY 1986 the principal effort was directed towards the fabrication and preliminary evaluation of experimental Mod II engines and components. The ASE program will be finished with the complete testing and evaluation of Mod II engines both in a dynamometer and in a vehicle using FY 1987 appropriations. Technology transfer activities have been expanded through Commerce Business Daily announcements and an outreach project at the NASA/Lewis Research Center to assure transfer of developed technology to industry and other government agencies, both through loan of Mod I and Mod II hardware and cooperative evaluation projects. Since this technology transfer will essentially accomplish the Federal program goals under our "proof-of-concept" strategy, we are not requesting funds for Stirling engine R&D in FY 1988.

The Heavy Duty Transport (HDT) Technology program focuses on establishing the technology base for future development of advanced adiabatic (low heat rejection) diesel engines. By eliminating or significantly reducing the size of the cooling system and recovering the increased exhaust heat, the diesel engine system becomes much more efficient and fuel flexible. The program consists of four R&D areas necessary for this development: (1) thermal insulation, (2) lubrica-

tion, friction and wear, (3) advanced thermomechanical systems, and (4) high temperature combustion and emissions. Single-cylinder test engines are used in the development of the basic technologies and components. In FY 1987 the final phase of the development of a heat transfer model for adiabatic diesel operation including engine test validation will be completed, and the second phase of the adiabatic diesel reference engine design effort will be continued. Experimental adiabatic engine emissions evaluation will be conducted, and ceramic coatings testing and analysis continued. New contracts will be initiated for high-temperature liquid lubrication development and innovative piston-cylinder configurations for the adiabatic diesel concept. In FY 1988 thermal barrier coatings development, advanced adiabatic diesel reference engine design, and emissions and combustion characteristics investigations will be continued. A project on piston-cylinder gas lubricated development will be initiated as will systems integration investigations to determine vehicle/propulsion system design parameters. A total of $2.9 million has been requested in FY 1988 for continuation of the Heavy Duty Transport Technology program.

Technology Assessment and Transfer is a continuing task needed to assess related developments by industry, and in other Government-sponsored programs, for use in program direction and to ensure that results from the program are conveyed to industry. Although maximum industry involvement is primarily accomplished through contractual participation, additional efforts are required such as annual Contractors' Coordination Meetings (CCMs), industry workshops where technological advances and future planning are discussed, and industry/academic oversight forums

where program goals, objectives, and results are reviewed. $470,000 has been requested in FY 1988 to continue these activities.

ALTERNATIVE FUELS UTILIZATION

The goal of the Alternative Fuels Utilization (AFU) program is to foster the use of nonpetroleum-based transportation fuels by establishing a technology data base for both contemporary and advanced heat engines. Emphasis is placed on synthetic fuels derived from oil shale and coal syncrudes. In addition, research on biomass-derived fuels and gaseous fuels has been done. AFU investigations of other fuel options, including alcohols, have provided an information base sufficient for understanding the implications of using the fuels in the transportation sector. Current work in this area involves monitoring foreign and domestic activities, facilitating technology transfer to industrial users, consolidating new data, and identifying critical open issues and selected R&D projects to fill data gaps.

The AFU program seeks to identify the fuel quality/engine design trade-offs for future reciprocating engines using efficient combustion techniques such as lean burn, stratified charge, or low heat rejection. Ignition quality fundamentals are being investigated, including definition of fuel-specification test procedures. Starting in FY 1987, the fuels will be evaluated in a single-cylinder research adiabatic diesel engine from the Heavy Duty Transport Technology program. Performance, emissions, wear and optimization investigations on other conventional and advanced engines using synthetic fuels will also be continued.

To assist the AFU program and other Government and industry researchers, a synthetic fuels supply center has been established at Southwest Research Institute. This center provides research quantities of a variety of realistic finished synfuels for utilization research projects, and is the only existing activity of this type. This activity will be continued during FY 1987.

An evaluation of Government fleet operations with methanol-fueled vehicles was initiated in FY 1985. The results of this evaluation will provide industry with both technical and operational data on which to make production and marketing decisions. During FY 1987, the evaluation of methanol-powered vehicle operations in the Federal fleet will be continued with three site locations in operation, including a cold-weather site. Between 20 and 25 methanol vehicles, with a similar number of gasoline-powered vehicles, are scheduled to be in operation by the end of this year.

In FY 1988, the data collection and analysis of the methanol-fueled vehicle fleet operations will be continued and performance, emissions and wear investigations on conventional and advanced engines using synthetic fuels will also be continued. "Second generation" coal and shale liquid will be integrated with the synthetic test fuels facility. A total of $1.1 million has been requested in FY 1988 for this program.

ELECTRIC AND HYBRID VEHICLE R&D

The objectives of the Electric and Hybrid Vehicle program are to: (1) conduct the research and development necessary to advance the technology to the point that transfer to the automobile industry for application-oriented R&D becomes feasible, (2) identify technology deficiencies of electric vehicles, and (3) evaluate the performance characteristics of new and improved technologies to determine their potential for resolving these deficiencies.

The primary focus of this program continues to be on the development of battery technology for vehicle propulsion. In FY 1987, development efforts will continue on an optimized flow-through electrolyte lead-acid battery concept, and on nickel-iron, iron-air, sodium-sulfur, nickel-cadmium, lithium-metal sulfide, and zinc-bromine battery technologies. The ongoing effort in the development of nickel-cadmium battery technology is focusing on lowering costs without sacrificing performance. The sodium-sulfur effort will continue with developing the technology for the electric vehicle application based on the core technology contract with Chloride Silent Power, Ltd. Additionally, during FY 1987, a request for proposal will be issued to seek a second source for the development of sodium-sulfur technology. The lithium-metal sulfide battery development effort is defining the battery attributes for the EV application and will be conducted in cooperation with the Tennessee Valley Authority and the Electric Power Research Institute efforts already underway. It is the intent in all of the battery developments to prove the capability of the full battery subsystem to function properly in a vehicle environment including

typical environmental, shock, and vibration conditions and realistic electric vehicle driving profiles.

In FY 1988 this program has been directed toward continuing the development of only the most promising of the battery concepts. Development of sodium-sulfur battery technology, including subsystem thermal management, will continue, and testing of a module incorporating sodium-sulfur cells optimized for electric vehicle application will be completed. Testing of the full proof-of-concept zinc-bromine battery will be initiated, incorporating optimized technology developed during the previous two years.

In addition to battery technology development, the program is also developing advanced electric vehicle propulsion systems. Within this area, two major programs are in progress: (1) the Second-Generation Single-Shaft Electric Propulsion System Technology Development Program (ETX-II), and (2) the Dual-Shaft Electric Propulsion Systems Technology Development Program (DSEP).

The ETX-II program is the second-generation of the ETX-I a.c. propulsion system completed in FY 1986 and includes an advanced permanent magnet motor and control technology for a light-weight commercial van application. In FY 1987, the detailed design of the ETX-II will be completed and transferred to industry. Since this transfer will essentially accomplish the Federal program goals, we are not requesting funds for ETX-II in FY 1988.

The DSEP program includes the development of advanced nickel-iron battery subsystem technology and is also focused on the light-weight van application. In FY 1987, development will continue including dynamometer testing of the powertrain performance and fabrication and test of testbed vehicles. With the funding requested in FY 1988 this program will be completed, including integration of the nickel-iron battery subsystem.

In FY 1987, the first phase of a fuel cell/battery powered bus system is being conducted. The emphasis of Phase I is on the design and development of a proof-of-concept fuel cell/battery subsystem for evaluation in a test-bed bus. The end result of this phase will be feasibility determination and a definition of the propulsion system configuration and design specifications. No funds have been requested in FY 1988 to continue this activity beyond proof-of-feasibility.

In FY 1987, testing and evaluation activities of electric vehicle technology include operational fleet testing and laboratory and in-vehicle dynamometer testing. Operational fleet testing by 10 site operators at 22 site locations is being conducted to evaluate vehicle performance and to collect engineering data on vehicles in the product improvement program. As part of the product improvement program by the Site Operators' User Task Force, Detroit Edison is continuing the on-the-road testing of the GM-Griffon van that utilizes long-life tubular-plate lead-acid batteries. In addition, the User Task Force will continue to produce, install and fleet test new technology components and systems that include improved nickel-iron and gel-cell lead-acid

batteries, flame arrestor devices, d.c. to d.c. convertors and fully integrated battery management systems. The fleet operational testing will be phased out after completion of the testing and evaluation of the product improvements program in FY 1987.

Laboratory and in-vehicle dynamometer testing will include the Eaton d.c., Soleq a.c., and ETX-I propulsion systems in test bed vehicles, and phase IV gel-cell and nickel-cadmium battery systems. Temperature sensitivity testing of batteries under development in the program is being evaluated in environmental chambers under various charge/discharge regimes. Performance and life cycle testing of nickel-iron, flow-through lead-acid, nickel-cadmium, zinc-bromine, and sodium-sulfur experimental batteries are being evaluated in controlled laboratory conditions at the National Battery Test Laboratory. Laboratory and in-vehicle dynamometer testing at the Idaho National Engineering Laboratory will be concluded in FY 1987.

The total funding request for the Electric and Hybrid Vehicle R&D program in FY 1988 is $3.4 million.

ADVANCED MATERIALS DEVELOPMENT

Improved materials technology is a key requirement in realizing the efficiency goals of the advanced engines being investigated. In particular, high temperature structural and insulating ceramics, and low friction and wear ceramics are needed. The technology for advanced ceramic materials is in its infancy. The goal of the Advanced Materials Development program is to establish an industrial technology base for

providing reliable and cost-effective structural ceramics for application to advanced heat engines. The program consists of a balanced research effort in three areas: (1) materials and processing, (2) data base and life prediction, and (3) design methodology.

The objective of the materials and processing research is to develop processing methods that can yield materials with the uniform microstructures and high temperature mechanical and corrosion-resistant properties necessary to meet the requirements of advanced engine components. Research on coatings addresses the lack of fundamental understanding in this area to allow the development of reliable methods for applying and characterizing coatings as well as for developing improved coating materials. Research on joining emphasizes developing a sound technology base for producing permanent joints having acceptable properties for structures of interest in advanced engines.

Research efforts in the data base and life prediction area are focused on the development of techniques, generation of concepts, and acquisition of data on both existing and improved ceramic materials necessary to improve mechanical and environmental reliability. Research in design methodology is oriented toward understanding the properties of brittle ceramics under stress well enough to predict accurately their lifetimes in specific engine-component uses.

During FY 1987, the phased activities on existing contracts and research projects will be continued essentially in accordance with the Ceramic Technology for Advanced Heat Engines Program Plan. Efforts will include

powder synthesis of silicon carbide and silicon nitride, ceramic composites using fibers and particles, ceramic coatings for thermal and wear, joining of ceramic to ceramics and ceramic to metals, study of contact interfaces, and life prediction for monolithic and composite ceramics. The International Energy Agency agreement on Ceramics for Advanced Engines and Other Conservation Applications with Sweden and the Federal Republic of Germany will be continued with emphasis on powder characterization, dense ceramic characterization and mechanical testing.

In FY 1988, research projects will continue in ceramic composite processing, thermal and wear coatings, joining of ceramics and time dependent behavior, as described above. We have requested $6.7 million for the Advanced Materials Development Program in FY 1988.

HIGH TEMPERATURE MATERIALS LABORATORY

To support the work conducted in the Advanced Materials Development program and other research programs, a user-oriented High Temperature Materials Laboratory (HTML) has been built at the Oak Ridge National Laboratory. The main advantages of a national facility for high temperature materials research are that it will: (1) strengthen interdisciplinary staff interactions, (2) provide a common focal point for industrial and university participation, and (3) provide access to high-cost research equipment which would otherwise be denied to many researchers.

The first of the scientific staff began occupancy of the facility in January ahead of schedule, and official operational status is scheduled

for April 1987. In FY 1988, $2.0 million is requested to support the 13 scientists dedicated to the user facilities and building maintenance and operations. Both proprietary user research with full cost recovery, and non-proprietary research at no cost to the user where results are immediately available to the scientific and industrial community, will be carried out at the laboratory.

PROGRAM DIRECTION

To provide the overall program direction of the transportation program including the development of the strategy, plans and resource reqirements, and integrated program management, we are requesting $1.5 million in FY 1988.

SUMMARY

In summary, the activities of the Department's transportation program cover a spectrum of projects structured to increase energy efficiency and reduce petroleum dependence in the transportation end-use sector. Although the program is focused on the transportation sector, the technologies under development for high-temperature materials, advanced propulsion systems, batteries, and alternative fuels utilization have a wide range of applications in addition to transportation.

That concludes my testimony, Mr. Chairman, and I thank you for the opportunity to appear before you today.

Mr. MCCURDY. When I said "summarize," you took it literally, didn't you? [Laughter.]

Thank you.

Miss FITZPATRICK. I could ramble on awhile, if you'd like.

Mr. MCCURDY. No, no. [Laughter.]

That's marvelous. You do have a rather definitive statement, and I think there are a number of issues that we'd like to cover, and actually it makes for a much more dynamic hearing when we have an opportunity to raise questions in those areas that we have individual concerns.

Let me start off with the—I'm sorry—do any of the other gentlemen have statements or comments? Okay.

On the AGT, the automotive gas turbine, what is the reason for proposing that the AGT ceramic component development program be reduced to a single cooperative effort, rather than continuing with two competing teams?

Miss FITZPATRICK. Mr. Chairman, this is driven principally by budget constraints. We have proposed reducing from two contractors to one. We think that a single contractor would be adequate to do the job. Both of the ceramic engines that are being run would give us the same technical information, and either one of them, we think, is quite capable of testing the components, which is the next phase of our research program.

Mr. MCCURDY. What do you think is the key technology breakthrough that will make the AGT a viable technology, ready for commercial development?

Miss FITZPATRICK. Learning how to mass produce the ceramic components with a high degree of reliability. We have an engine design that works. We have a good idea or have found the composition, or very nearly the composition, of the ceramics that should go into it.

Our problem is that we cannot mass produce those components and have a—be able to assure their quality.

Mr. MCCURDY. So it's not a commercial—is there any commercial entity in the United States that has the capability to produce at reasonable cost, reasonable levels?

Miss FITZPATRICK. No. At this point, we know of nobody who can make these components, even on an almost one-by-one basis, and have them survive in the engine. The ultimate goal, breakthrough, will be to do that, plus be able to mass produce them.

There is, though, a very large increase in the number of companies who are getting into the ceramics field and making their own investments in it.

Mr. MCCURDY. Such as?

Miss FITZPATRICK. There's a—we have—well, our experience in the last few years has been, when we tried to get people to come to meetings and review sessions to talk about ceramics, we might get two or three suppliers to show up. We now get in excess of a dozen, fifteen or more.

There is a very great interest, more private investment, and much better communication between the engine manufacturers and the ceramic supply industry.

Mr. MCCURDY. Is there any international firms that produce what you consider to be a viable ceramic technology that is commercially feasible?

Miss FITZPATRICK. We have obtained some components from Japanese companies, but none of them yet have been able to hold up in the engine. So they don't appear to be ahead of us in that.

Mr. MCCURDY. They don't appear to be commercially viable at this point?

Miss FITZPATRICK. That's right.

Mr. MCCURDY. Or ahead of us in technology?

Miss FITZPATRICK. Nobody is commercially viable at this point.

Mr. MCCURDY. The proposed budget for vehicle propulsion suggests funding a single testing rig instead of the two currently operating.

Are there any technical reasons for not continuing the program with two test rigs?

Miss FITZPATRICK. No.

Mr. MCCURDY. I stress the word "technical."

Miss FITZPATRICK. Yes, sir. No technical reasons.

Mr. MCCURDY. Is it again just cost or the budgeting dilemma?

Miss FITZPATRICK. Yes.

Mr. MCCURDY. Which is again rather difficult for this member, who sits on the Armed Services Committee, to understand some of the lack of priorities here.

What was your overall budget request—how much were you cut from—it's 60 percent less than fiscal year 1987?

Miss FITZPATRICK. Yes, sir, that's about right. It's $56 million appropriated for 1987. We have a request of $22.4 million.

Mr. MCCURDY. Right. Now I would assume that is not what you requested within the Administration?

Miss FITZPATRICK. That's true.

Mr. MCCURDY. Did you request more than you had appropriated for fiscal year 1987?

Miss FITZPATRICK. No, sir.

Mr. MCCURDY. Did you request the same amount that you had in fiscal year 1987?

Miss FITZPATRICK. We requested less, largely in the areas of the Stirling engine and the electric vehicle battery programs. We requested more in the gas turbine program.

Mr. MCCURDY. So gas turbine was a higher priority at least within the agency?

Miss FITZPATRICK. Yes, sir.

Mr. MCCURDY. But OMB didn't share the same concern for priority?

Miss FITZPATRICK. Their conclusion was that we did not need a second contractor in the gas turbine program.

Mr. MCCURDY. Do you agree with that?

Miss FITZPATRICK. I agree that, from our point of view, from the energy point of view, we would like to have the second contractor. We believe that that is the optimum program. From a budgetary point of view, OMB has to make those decisions, and that was their—after weighing their concerns, that's what they came up with. And we agree that we can operate an adequate program that way.

Mr. McCURDY. If you were to receive an appropriation at a rate higher than what the current request as submitted—where would you prioritize or what would your priorities be?

Would you—can you give us an outline of the areas that—say, if you had the level that you had in fiscal year 1987, $55 million as opposed to the $22 million, would you roughly keep the program as we saw last year, or how would you change it?

Miss FITZPATRICK. I would put as my first priority a second contractor on the gas turbine; next, to restore some of the funds that were cut from the advanced materials program. In the batteries area, I would start work on a lithium metal sulfide battery, not continue some of the—we are asking for funding for sodium sulfur and zinc bromine. I would continue those. If I were to start a new battery, it would be lithium metal sulfide.

Those are the priority areas. I might restore a little to the adiabatic diesel engine.

Mr. McCURDY. I'm sorry?

Miss FITZPATRICK. The adiabatic diesel engine could stand to have a little bit more funding.

Mr. McCURDY. Did OMB in their justification to you indicate that it was their feeling that, since this was an area that the private sector was becoming more interested in, that they should fund it themselves?

Is this—we have somewhat of a privatization philosophy within—certainly within OMB, maybe not the other agencies of the Government, but certainly within OMB.

Was that the general argument that was used, or was it just general budget considerations?

Miss FITZPATRICK. It's both of those arguments. I think probably the general budget pressure drives a lot of other arguments, but that's—it may be the overriding one. But they certainly also point out that there is growing private sector interest and investment in this area.

We have to agree with that. The question really is, how fast is that growing, and what is the best way to nurse it along?

Mr. McCURDY. Right. And it is your learned opinion that we're not at a stage to make this commercially viable, or is there sufficient justification for, quote, "privatization?"

Miss FITZPATRICK. No, not quite. My opinion is that the budget we have requested is adequate; it is not, from a strictly energy point of view, the optimum program that we would like to carry out, if we did not have budget constraints.

I'm also very aware of things that we can't do because we have a deficit, and we need to get the country out of that situation.

Mr. McCURDY. Well, I agree with you. But also comparing with other areas of jurisdiction, I question what some of the priorities are.

Let me ask one other series of questions, and then I will certainly turn to our colleague.

The compressed natural gas vehicles, where do you see them as far as maturity, and do you believe that they are fully at a commercial stage, and there's nothing more that your agency can do?

Miss FITZPATRICK. We participated over the last three years with the American Gas Association in publicizing the compressed natu-

ral gas vehicle. They had two cross-country tours, and I think we were probably present with a DOE representative at more than half of their stops around the country.

That technology is commercially available. We have done a small amount of further work in studying some of the fine points of contaminants in the natural gas, what effect do they have on the engine, that kind of thing. But it is commercially available, and it does show a large opportunity in certain niches of the market, especially in fleet operations.

Mr. MCCURDY. Some of the proponents of that concept, however, are still arguing that there is a need to design an engine expressly for natural gas, and that there needs to be work on the engine storage tanks, engine compressor, and engine efficiency, startup capability, as an example.

Do you disagree with their concern?

Miss FITZPATRICK. I agree, there probably would be some benefit in finetuning certain parts of the system, as you mentioned, but it is basically a commercial technology, and it would have to come as a rather low priority in our program.

Mr. MCCURDY. Do you believe that these areas become more commercially viable when the price of oil eventually gets up to, as we in Oklahoma might say, "more reasonable prices?" [Laughter.]

Some others might say "a higher price" for oil and gas.

At what point do you believe that some of these technologies become more of an investment for the commercial sector, or a better investment?

Miss FITZPATRICK. Well, obviously, you're correct that the more expensive oil is, the more attractive alternatives will appear to be. Gas prices may follow oil prices, though, so you have to be a little bit careful about that.

It's difficult to say without going through each technology where the turnover point is against the price of oil. Obviously there has been some complacency in some minds—I don't think in the Department of Energy's—about the need to pursue alternatives, when we have at present rather low prices and a glut in the oil market.

I think the proper thing for all of us to do is to continue on a steady, long-term research program that will eventually give us fuel flexibility at whatever the foreseeable cost of oil is at some point in the future. Eventually the price of oil has to trend upward.

Mr. MCCURDY. Well, my colleague from Louisiana, I'm sure, would agree with you.

The point I want to get to, though, is, are you personally satisfied—and I'm, you know, I'm not trying to put you on the line; I'm just trying to get a statement from the agency—are you personally satisfied that the program and the budgeting for that program, as outlined, is a sufficient priority to set this country toward energy independence, in light of the future threat of cutoffs or increasing oil prices?

Miss FITZPATRICK. Mr. Chairman, I'm not sure that any long-term research program can address the problem of a cutoff, which could come at any time. We can address the problem of the eventual decline in the supply of oil and the eventual need to shift our economy and transportation sector, in particular, to some other fuel source. And I think we are on a solid road to doing that.

Mr. McCURDY. Not the optimum road, but a solid road?

Miss FITZPATRICK. That's right.

Mr. McCURDY. A minimum floor which would be solid?

Miss FITZPATRICK. That's right. You took the words right out of my mouth. [Laughter.]

Mr. McCURDY. Mr. Lewis.

Mr. LEWIS. Thank you, Mr. Chairman.

I'd like to talk a moment or two about the Stirling engine. Last year, we appropriated about $8 million for that, and this year we're not appropriating any, and the critics of this action say that additional funding is necessary for transfer of technology to the private sector.

Does the Department of Energy agree with this?

Miss FITZPATRICK. Mr. Lewis, that program has been carried out by a private contractor. This has been planned as the final year for the development and testing of the Mod 2 Stirling engine in a vehicle.

I think that part of the problem has been a very small interest on the part of any other private sector entity in using the engine for automotive purposes. If there is interest in doing that, it's certainly in the best interests of the contractor to want to fund that itself or to have its future market purchaser funded.

But I think the Government has already put a great deal into this, and it's about time that somebody else showed that they cared about it.

Mr. LEWIS. Has DOE been approached by any other automotive manufacturers for the use of the Stirling engine, or any manufacturers?

Miss FITZPATRICK. No. It's been the opposite. We've contacted more than 50 potential users, not just for automotive purposes, but for other purposes such as pumps and electric generators. We've been out trying to sell the thing.

Mr. LEWIS. Are you familiar with the performance parameters of the engine at this point in time? It did have an acceleration problem a couple of years ago. Does it still have that? Has it overcome that?

Miss FITZPATRICK. It has met all its performance specifications for fuel efficiency, emissions, acceleration, et cetera.

Mr. LEWIS. In a dialogue with the chairman, you discussed energy independence and a minimum floor. I have great concern personally that we're still not doing anything, or enough of what we should do, to provide ourselves with alternative fuels.

I don't believe that the petrochemical industry is doing that as well.

What I have noticed over the past few years, we've seen a gradual decline in any work in the alternative fuel programs.

Does the Department of Energy feel that this is not a priority program that your Department should be addressing and the Federal Government should be addressing? Or do you feel that the petrochemical industry should address that on their own?

Miss FITZPATRICK. I think that there is an interest in alternative fuels. The one that comes up most often is methanol. Methanol now is made almost exclusively from natural gas. The thought is that eventually you could make it from coal.

It is not economically competitive with petroleum at this point, even methanol from natural gas. If you make it from coal, it's even more expensive. And that's why there is not a great shift to using methanol.

But the long-term view seems to be, from talking to people in the automotive industry, that they—many of them would expect that methanol is the post-petroleum fuel, and there is some work going on in lowering the production costs of methanol, which, of course, would be a very great step and in looking at what a methanol engine should be like, what is the optimum engine design.

There has been some work done on simply adapting gasoline engines to methanol, and, in fact, the Department is running a number of vehicles, test vehicles, using methanol.

Mr. LEWIS. In your position with the DOE and with the very fragmented organization of OPEC at this point in time—and it looks like they, again, are having problems—what if they got together the 1st of April and put an embargo on us? How would you address that?

Miss FITZPATRICK. First, we have the strategic petroleum reserve——

Mr. LEWIS. Which we haven't been filling very well.

Miss FITZPATRICK. Well, it now has some 530 million barrels in it, which is about a 120, 130-day supply of our net imports [See correction 1 in appendix.] Of course, we get a rather small proportion of our imports from the Persian Gulf countries. Our biggest suppliers are Canada, Great Britain, Venezuela, and Mexico.

So even if OPEC put an embargo on us, we would be able to meet, from what we can deliver from the strategic petroleum reserve, that difference.

Our European allies might have a different problem. They, in general, don't have as high reserves as we have, and they tend to be more dependent upon OPEC.

Obviously, it would be disruptive to some extent.

There is also the factor that exists today, that didn't exist to such an extent twelve years ago, and that is that those countries need to be selling oil. They have made investments and commitments and gotten used to a standard of living in the last ten years that they didn't have before. And I think we saw that last year when there was a move within OPEC to cut production in order to force the price back up. It caused Sheik Yamani's retirement and some rather startling reactions within OPEC.

So the problem has been not that OPEC is going to cut to such an extent as to embargo, but simply to keep production down to something where the price doesn't collapse under them completely.

Mr. LEWIS. Well, Mr. Chairman, I don't want to delay on this.

Mr. Chairman, if we continue to see this problem with OPEC and we continue to have some sort of glut of fossil fuels, and the price of oil per barrel continues to drop—we got into a very dangerous situation just a couple of months ago——

Miss FITZPATRICK. Yes.

Mr. LEWIS. Some of the suppliers other than OPEC that you mentioned would just tell us where to go about the loans, because they won't be making the money to pay their loans.

Does that still mean we're going to be—how would we continue to receive fuel from them, when the oil—they can't meet—oil, say, goes to $10 a barrel——

Miss FITZPATRICK. What would happen then?

Mr. MCCURDY. $18 is a magic number. $10 puts them in real trouble. And it was dangerously close to $7.50 a barrel just two months ago.

Miss FITZPATRICK. That's right. And at $10 a barrel, there are some of our suppliers who—that's lower than their lifting cost. That's true. It tends to be about $12 a barrel in the North Sea, for example. I think Alaskan oil——

Mr. MCCURDY. 25 sounds real good in Oklahoma. [Laughter.]

Miss FITZPATRICK. Well, I think everybody can agree that low oil prices are not an unmitigated blessing by any means.

I wish I had some good answers, simple answers to your questions, Mr. Lewis. They're serious concerns.

Mr. LEWIS. Well, I guess I'm just concerned that—and this question certainly is not in total line with the hearing—but the DOE has not really stepped up to the responsibilities, I think, of getting us oil independence. And I believe that we got complacent, and I'm afraid—I'm very much afraid that within the next 36 months we might again be standing in lines, the way the situation is going.

Whether OPEC needs to sell their oil or not, I just think that the price of oil could go dangerously low and also hurt our competitors from the South or our suppliers from the South, and they're not going to meet their obligations as well.

I just don't know whether the Department of Energy has really reached the potential it should, as far as coming up with alternative systems.

Sooner or later, we're going to run out of this fossil fuel. There ain't no way. No doubt about it, we're going to run out of it, and we'd better have something else to run on.

And that takes me into electric vehicles. What does the DOE think is the future of electric vehicles in this country?

Miss FITZPATRICK. We think it will be possible to manufacture electric vehicles that will meet a large portion—it's impossible to say how large—of our vehicular needs. We are working on electric vehicles that will have a range in excess of 100 miles per charge. This is obviously not an over-the-road, cross-country vehicle. But for a lot of the urban driving that goes on and especially a lot of the fleet car use, it would be a very competitive vehicle.

It would also do a great deal in another important sector of our energy economy, and that's the electric utility system. It would help to keep—since those vehicles would usually be charged at night, it would help utilities to keep their generating capacity in optimum use over the 24-hour cycle, instead of having a peak in the daytime and then very low use at night.

And then, in effect, you might be running electric vehicles on coal, since that's our major electricity generator fuel.

Electric vehicles, though, are going to have to solve the basic problem, which is batteries, and that's what our program is aimed at. We've been working with various types of batteries for a decade or more, and we think we've narrowed it down to the two that show the greatest promise, sodium sulfur and zinc bromine, and

that's what our request covers, to get those batteries up to a commercially viable stage.

Mr. LEWIS. You reduced your budget this year by 66 percent below last year's in the electric vehicle program. What high-risk programs have we cut out, or how can we continue down the path that we were, looking for a reasonable battery, to get rid of the lead battery?

Miss FITZPATRICK. What we have reduced, Mr. Lewis, has been a number of different kinds of batteries that we think don't have—either have reached their optimum development or don't show the potential of meeting the needs of an electric vehicle. So we have done that in order to concentrate on the two that we do think will satisfy our criteria.

And we have also reduced the support that we have been giving to a number of private companies that are operating electric fleets and are finding them to be good vehicles. We think that they can pick up more of the cost of operating those fleets.

Mr. LEWIS. Thank you, Mr. Chairman.

Thank you, Miss Fitzpatrick.

Mr. MCCURDY. The gentleman from Louisiana, Mr. Hayes?

Mr. HAYES. Yes, thank you. I know that I came in a little late, but one of the things that has concerned me about being a freshman Congressman is, I didn't really expect to know anything, and it didn't bother me that witnesses, with their tremendous involvement in a particular subject, would know a great deal more than I did, until this afternoon when I just heard you, because I don't know a whole lot about oil and gas, but I'm going to tell you something: We'd better spread our educational levels around.

In the first place, the 530 million barrels in the strategic petroleum reserve does not compute liftup price. I have in my district Hackberry, Louisiana. Hackberry is a strategic petroleum reserve, but there's no pipeline to the refineries.

Now if the price is $45 tomorrow afternoon, you're still going to spend forever trying to lift out of Hackberry, Louisiana, and you're not able to compute those numbers as if you can turn a faucet on and off and have that raw product there.

How in the numbers are you computing liftup cost when you're looking at projections in price and the use of the strategic petroleum reserve, are you figuring on the number of days of reserve, or are you assuming an instant refinery delivery?

Miss FITZPATRICK. I'll be first to grant you, Mr. Hayes, that you may well know more about this than I do. I am going on the information that I have been given in the Department, that we have a lifting rate of 3 million barrels per day in the strategic petroleum reserve.

I grant you, I do not know what the costs are or whether there are pipelines from certain reserve sites directly to refineries.

Mr. HAYES. Originally the pipeline was in the budget, but it wasn't completed. And what I wonder is, when they're figuring delivery, I wonder if they're assuming there's a pipeline that's there that is not, in fact, in place, because in the wayside of additional budget constraints, it was never constructed.

That's something I don't know. Maybe both of us ought to find out.

[The information from DOE follows:]

STRATEGIC PETROLEUM RESERVE DRAWDOWN CAPABILITY AT THE WEST HACKBERRY SITE

The Strategic Petroleum Reserve storage site at West Hackberry, Louisiana has a fully operational drawdown capability which would now permit 1,400,000 barrels per day to be pumped through the Federal Government's pipeline to the Sun Terminal in Nederland, Texas. In recent years, it has been recognized that the conversion of the Texoma crude oil pipeline to natural gas transmission has limited the Department's ability to distribute the oil from Sun Terminal at previously planned rates. Therefore, the net distrbution capability for West Hackberry has been rated at 1,200,000 barrels per day.

To increase this net distribution capability to the full site drawdown capability and also to accommodate the development of another storage site, Big Hill, the Department has started design and land acquisition for a second pipeline from West Hackberry. Funding for the construction of this second pipeline, which will transport oil to refineries and marine facilities in the Lake Charles, Louisiana area is included in the Department's budget request for fiscal year 1988.

During a drawdown of the Strategic Petroleum Reserve, the major elements of costs are expected to be electric power charges, terminalling fees, and additional site manpower for operations. The Department's most recent estimate is that the cost to draw down 500 million barrels would be approximately $54 million, or about 11 cents per barrel, in addition to normal standby operating costs.

Mr. HAYES. And secondly, I'm concerned in looking at our cost of deliveries—when we speak about the Northeast, where the gentleman to my left is quite concerned—No. 6 crude is something you can shovel at 40 degrees. It's our fault for talking about oil and gas as if they're the same thing, because they're not remotely the same thing.

And I wonder what anticipation we've made in energy policy with the realization that you can't import gas, and that the only manner that has remotely been attempted in the past at importing gas ended up with a tanker supply cost of well over $7.20 for a million cubic feet. That's a gas price that would make New England once again throw tea in the harbor.

What anticipation has been made that the gas price has got to be studied independent of OPEC and oil price, because OPEC is never going to put a gas embargo against us?

Miss FITZPATRICK. Right. They can't.

Mr. HAYES. That's not—that's not a feasible alternative. What are we doing in light of separating those two for an understanding of energy cost and for home heating cost?

Miss FITZPATRICK. I think that's an area that our Fossil Office would have to answer for you, and I'd be happy to have them answer it for the record.

[Information to be furnished follows:]

Although imports of Liquified Natural gas (LNG) have not been competitively priced in recent years, price renegotiations could make this source of natural gas attractive. The United States currently imports approximately 5 percent of its domestic gas consumption from Canada at competitive prices.

The Department recognizes that although the sources of oil and gas supply are often different, their end-use markets are interrelated. Oil and gas currently compete on price in the industrial boiler fuel markets, for example. In the case of residential markets, natural gas is generally purchased by pipelines under long term contracts. Prices under these contracts adjust relatively slowly to changes in oil prices, but over a period of years, a significant increase in world oil prices would be reflected in higher residential gas prices.

Mr. HAYES. And then when we get into—tell me a little bit of background, and I apologize for this, because I would like to—I would not like to burden you with this, but if you could just in a moment—on the Stirling engine, would you give me, in just a moment of your time, the design concept sought being advanced? In other words, why did we fund it in the first place? What technology were we seeking?

Miss FITZPATRICK. The Stirling engine has potentially, theoretically, a thermal cycle that is about as efficient as we could hope to get. So it was funded in search of fuel efficiency and also fuel flexibility. It doesn't have to run on gasoline. It's an external combustion engine, so you could burn almost anything to get the heat to run it.

Mr. HAYES. And if I understood Mr. McCurdy's question as I came in the room, apparently this comes under the compressed gas budget?

Miss FITZPATRICK. No.

Mr. HAYES. But it's not included in a request for funds?

Miss FITZPATRICK. No, sir. It's been under the vehicle propulsion budget.

Mr. HAYES. I see.

Miss FITZPATRICK. No particular fuel specification. And we have not requested—we are, this year, finishing the planned program for the Stirling engine, and we are not requesting further funds for it.

Mr. HAYES. And if I followed the earlier comments, in other words, you put it out into the marketplace under the feeling that it's advanced to the point where private industry should then become involved?

Miss FITZPATRICK. That's right.

Mr. HAYES. Do you think under—if we just assume no ups or downs and can only deal with today—under present price levels, do you think the technology is advanced enough to bring private industry in under today's price?

Miss FITZPATRICK. I don't think that the Stirling engine, for an automotive application, is ever going to be very attractive. It's too expensive. I think we have better alternatives.

One of the things that concerns people is that the working fluid in the engine is hydrogen, and that's a very tough thing to handle. Hydrogen leaks, hydrogen explodes, hydrogen would have to be stored at service stations in order to restore the leaked hydrogen in engines. People don't like to store hydrogen. But if you don't have hydrogen in there, the engine loses its efficiency.

Putting hydrogen in an engine which has to be on a vehicle, subject to vibration, dirt and everything else that people do to their cars is a worrisome thing.

Mr. HAYES. So if I were to conclude, it might be more correct to say the position that you have is more that there's a question in your mind as to the feasibility of the research, rather than that you feel the research has gone far enough for private industry.

Miss FITZPATRICK. We think the research in the engine development has gone far enough for industry to make a decision about whether they would like to use this engine in a vehicle. So far we have seen little or no interest on the part of the industry in using it.

The engine does have applications in other areas where you could protect it from vibration and service it more conveniently, such as water pumps, electric generation. We use it ourselves in some of the other research programs that we carry out, solar thermal electric generation or heat pumps. But we don't see an application in the automotive industry.

Mr. HAYES. Okay, thank you, Mr. McCurdy.

Mr. MCCURDY. I thank the gentleman.

The gentleman from Wisconsin, Mr. Sensenbrenner.

Mr. SENSENBRENNER. Thank you, Mr. Chairman.

First of all, let me state for the record that not all the members of the subcommittee think that $25-a-barrel oil prices is a great idea. I won't put it to a vote, however. [Laughter.]

I do have a couple of questions, Miss Fitzpatrick, specifically about the DOE electric vehicles program and research funds on new battery development.

Of the $3.4 million that is in the budget request for the electric vehicles program, how is that split down into new battery development, and further, how is the new battery development money proposed to be spent?

Miss FITZPATRICK. Mr. Sensenbrenner, could I ask Mr. Streb, our Deputy Assistant Secretary? He has those figures.

Mr. SENSENBRENNER. Surely.

Mr. STREB. Mr. Sensenbrenner, the battery development work is divided into two parts. There's $1,300,000 going into sodium sulfur batteries and $500,000 into zinc bromine batteries. So we're supporting in this year's budget just two advanced battery systems.

Mr. SENSENBRENNER. Now how does that compare to what happened in last year's budget?

Mr. STREB. In last year's budget, in addition, there were a variety of other advanced batteries that were supported, including lithium metal sulfide, (nickel-cadmium), iron air, and one or two others, which required about $3 million of support. And in addition, we supported development of evolutionary technology on lead acid and nickel iron batteries.

Mr. SENSENBRENNER. Why have the battery types that you have been talking about been proposed for zeroing out in this year's budget?

Mr. STREB. Insofar as the advancement of existing batteries, such as lead acid, we feel that the technology is far enough along that industry should support that on its own and insofar as advanced batteries are concerned, we chose the two that we felt had the greatest chance of giving us the performance that we were looking for, and that was the zinc-bromine and sodium sulfur.

Mr. SENSENBRENNER. How long do you anticipate it will require to do the Government research on these two types of batteries? Is this the last year or do you anticipate this going on for some more years?

Mr. STREB. No. I think we are probably looking forward to a minimum of three years on each of these battery systems and perhaps more. There's considerable technical work that needs to be done.

Mr. SENSENBRENNER. Do you know of any companies in the private sector that are going to be picking up the research on those

battery types that are proposed to be discontinued in this year's budget?

Mr. STREB. I'm not aware there is any company that is committed to picking it up. I think there are companies that are working on it. Gould, for one, is doing some work on lithium metal sulfide, which by the way is receiving support from other sources. TVA and EPRI are putting a small amount of money into those battery systems, into that particular battery system.

Mr. SENSENBRENNER. Well, with all of the other battery systems that you have been talking about zeroing out, what's happening? Are those just lapsing and the money that has been appropriated so far is just down the chute?

Mr. STREB. I think that we have made great strides on lead acid and the other near term batteries. I think the gel-cell lead acid, for example, is here today as a commercial product largely as a result of the effort that we've put into it. So there has been some success and I think, with respect to the advanced battery systems, part of the conclusion of the work that we have done so far is that perhaps the risk is too great to continue to pursue, at least in the case of one of the advanced battery systems.

Mr. SENSENBRENNER. I would like you really to submit some written testimony for the record about what the status is of the proposed systems that are discontinued in the budget request that the Administration has sent up, because certainly we don't want to throw any good money after bad, but at the same time, I'm a little bit concerned that some of the systems we might be leaving in the lurch, since you only mentioned one that the private sector is picking up immediately.

So, I would like to have a little greater detail on why all of these proposed systems that we have been funding in the past are being discontinued. I think the Subcommittee would need that in its consideration of this issue.

Mr. STREB. We'd be happy to address each and every one of them, sir.

[Information to be furnished follows:]

STATUS OF DISCONTINUED BATTERY CANDIDATES

Flow-Through Lead-Acid Battery—An advanced lead-acid battery for electric vehicles is being developed by Johnson Controls, Inc. (Milwaukee, WI) under a four-year, $3.3 million, DOE-sponsored development contract initiated in December 1985. JCI, the world's largest manufacturer of automotive batteries, also provides a significant cost-share of the contract costs (greater than any other DOE-sponsored battery development effort). The objective of the R&D effort is to improve the performance and life of lead-acid batteries. The work is based on an innovative concept whereby a forced flow of the electrolyte through the porous lead and lead dioxide electrodes is employed to achieve a dramatic increase in the utilization of these materials. Based on this concept, JCI has fabricated proof-of-feasibility flow-through cells. These first-of-a-kind experimental cells, which were independently evaluated at Argonne National Laboratory, demonstrated the viability of the concept by achieving very high levels of material utilization (85% greater than that obtained in commercially-available lead-acid batteries). This quantum leap in utilization provides an opportunity for a major increase in the energy density, and therefore electric vehicle range, provided by lead-acid batteries. In 1987, the R&D effort is being directed towards extending the useful life of these cells to several hundred charge/discharge cycles. The end result of this R&D contract will be the fabrication and delivery of full-size battery systems These practical, low-cost batteries are expected to provide a 75-mile range on the Federal Urban Driving Schedule (FUDS) for an electric van. This battery couple has limited energy density and power compared to sodium-

sulfur and zinc-bromine couples. This technology will require high maintenance, therefore the department did not request funds for FY 1988.

Lithium/Iron Sulfide Battery—Design studies funded by DOE/EHP over the past several years have shown the Li/FeS to be a viable candidate for application to electric vehicles. As a result of these studies, a group consisting of EPRI, DOE, TVA, ANL and Gould, Inc. has been formed to examine the feasibility of developing a Li-alloy/FeS battery for an electric van. The funding for this project has been supplied by EPRI, TVA, and DOE. The work being carried out by a close collaboration between ANL and Gould. The van battery project has progressed to the point where a 12-V battery module has been successfully tested, a 36-V battery is undergoing tests at ANL, and a joint EPRI/DOE program has been initiated to fabricate a 108-V battery. DOE is providing $290,000 in FY 1987 to develop and fabricate an insulated case for a 108-V battery. This technology is being funded by the Electric Power Research Institute and the R&D is of a near-term nature that should be within the risk-payoff criteria of private sector investment.

Iron/Air Battery—A 5-year contract with Westinghouse Electric Company to develop iron/air batteries is now in place. INEL is administering this contract which has a total value of $5,544,000. The government share of the contract is $4,659,000, with the balance being Westinghouse's cost share. The funding level of this contract for FY-87 is $470,000 and the level of effort identified in the FY-87 program plan will consume all appropriated funds. With this level of effort, Westinghouse is projected to complete the iron and air electrode development activities and produce a prototype cell design. The actual fabrication of three prototype cells for independent testing will be completed at the end of FY-87. This technology has limited power capabilities and may not be suitable for EV application because of its short cycle life. Therefore the department did not request funds for FY 1988.

Nickel-Battery Types—The major problem with nickel material based batteries is the first cost to the consumer. Other aspects of the nickel battery in need of improvement are specific power, specific energy and a reduction in maintenance routines and associated costs. In FY 1987, $400,000 was allocated from appropriations for conducting research and development on a thick nickel electrode nickeliron battery. The objective of this research is to cost reduce the nickel electrode technology through fewer required electrodes and therefore less nickel material. Eagle Picher completed fabrication of it's first 2.9 MM thick sintered-nickel electrode and delivered an operating module for test to Argonne National Laboratories, January 30, 1987. A new fiber nickel technology has been introduced into the FY 1987 Eagle Picher research program to mount a two front effort to achieve the cost reduction objective. First test results with 50% fiber 50% nickel powder yielded a material utilization comparable to sintered slurry technology. The fiber electrode is structurally stronger and has 50% higher electrical conductivity.

Testing and evaluation of the feasibility of the thick electrode technology to reduce the cost of the nickel-iron battery will be completed using FY 1987 funding. A more in depth analysis of the potential benefits of the fiber nickel structure could be pursued in terms of it's 50% higher conductivity, higher structural strength and increased capacity per unit weight by direct activation of the nickel fiber to further reduce the amount of nickel required in a cell or battery. However, this activity is well within the reach of industry so additional funding is not necessary.

For FY 1987, $1.250 million was appropriated for completing research and development on roll-bonded nickel-cadmium batteries for electric traction applications. The three year Energy Research Corp. contract was restructured to concentrate on the roll-bonded nickel electrode, the remaining serious problem in the technology development. An integrated test program was also initiated to aid in early definition of the problem and to assist in accelerating it's solution.

Fiber nickel electrode material could be evaluated in this battery type for cost and performance improvement. The current technology will likely be marginal in power, storage capacity and life making it's cost effectiveness questionable. However, this activity is well within the reach of industry, so additional funding is unnecessary.

Mr. SENSENBRENNER. Thank you, Mr. Chairman.

Mr. MCCURDY. That's a reasonable request. The gentleman from New Mexico, Mr. Lujan.

Mr. LUJAN. Thank you, Mr. Chairman.

I'd like to follow up on the engines a little bit. Your response was that they won't work in automobiles because of the hydrogen and the escaping and the chances of explosion and all of that. We didn't

set out to do the Stirling engines so they could be used in automobiles?

Miss FITZPATRICK. We set out to do the Stirling engine for automobiles and to try to solve all of the problems which were admitted from the start, the automobile application would be the hardest one to solve because of the weight and volume restrictions, because of the vibration and dirt that automobiles are subject to.

If you could solve those problems, our position really is that those problems might conceivably be solvable, some of them, some things are better than they used to be, for example, with the leakage problem, but the cost of doing that, what you have to do with the engine makes it hardly worth the effort. We simply think we have better alternatives if we want a highly efficient flexible fuel engine.

Mr. LUJAN. Is the Stirling engine ready for use like a motor, to bring water up from a water well?

Miss FITZPATRICK. We understand there has been some commercial interest in water pumps, also in electric generator sets. As I mentioned, we are using it—exploring its use in heat pumps. We will be putting one into operation on a solar thermal electric generator this summer. The engine has an efficiency cycle which is very attractive. It makes it worth looking at, if you can keep it in an environment where you can in a sense protect it.

Mr. LUJAN. Like inside a building?

Miss FITZPATRICK. That's right. Running it around on the road and having remote service areas, as we would be accustomed to have with an automobile, can be a problem.

Mr. LUJAN. Do you think it is ready for those uses that you mentioned, that can be done?

Miss FITZPATRICK. It's undergoing development for those uses now.

Mr. LUJAN. Why are—I understand people are coming to us for more money, not the Department of Energy, but I guess for the work on the development. What do they want more money for?

Miss FITZPATRICK. I guess what everybody wants more money for. I suppose they believe in the engine and think they can market it, and I say, fine, go ahead and do it, but we haven't been able to find people who are interested in putting their own money into further development for it. There has been some work by John Deere totaling about $160,000. Last year in the appropriation, Congress said that it expected that industry would come up with $4 million of its own to match the $8 million that Congress appropriated, and we haven't seen any of that $4 million except what John Deere came up with.

Mr. LUJAN. So it's really not ready to be commercialized; is that what you are saying? Even for those stationary uses?

Miss FITZPATRICK. No. Nobody is ready to go into commercial production on it; no. Not that I know of.

Mr. LUJAN. How close are we to finishing our research on ceramic engines?

Miss FITZPATRICK. The ceramic engine itself is designed and runs at temperature and at the revolutions, one of them at 80,000 rpm and the other at 100,000 rpm, that they were designed to. They have met their efficiency and emissions specifications. Our problem

now is to learn how to work with ceramics in order to make reliable, large production runs of the components. What goes into that engine in particular are the turbine rotor itself, which is the most complicated and I guess the piece that is under the greatest stress.

Our ceramic engine program now is concentrating on that ceramic component development, and that's going to take several years anyway.

Mr. LUJAN. You mean to produce the ceramic, the type of ceramic that you need for that engine in large quantities? Is that the problem?

Miss FITZPATRICK. The handling of ceramics is really a cutting edge technology. Nobody really knows how to handle these materials in a production fashion. It's difficult even to handle them in the laboratory and make a component that will stand up to the stresses that we put it under. We haven't really succeeded in doing that consistently.

We need to know better the exact chemical composition of the ceramic, its structure, whether it should be made a composite with one kind of a ceramic and a matrix and little pieces of other types embedded in it. We need to know then how do you manufacture that, how do you put it into a mold, how do you fire it, how do you handle it throughout the manufacturing process, and those questions really go to the basic understanding of the material itself. It's not simply an engineering problem.

Mr. LUJAN. I'm just a little bit confused because I understood that you told me at the very beginning that we have already run these ceramic engines and they do what they are supposed to do. I gather there is one or two out there already chugging away.

Miss FITZPATRICK. There are two different models and they run. What I'm saying is the engine itself runs—certain pieces of the engine don't stand up yet to the thermal and mechanical stresses that you put them under, but the overall engine design, we know how to do.

Mr. LUJAN. Okay. Thank you very much.

Mr. MCCURDY. Thank you, Mr. Lujan.

Madam Secretary, the Committee in the DOE authorization report language last year requested the Agency, DOE, to establish a long term program plan in advanced structural ceramics R&D. Where is that plan?

Miss FITZPATRICK. Mr. Chairman, there was also instructions to establish not for us but for the Executive Branch to establish a National Critical Materials Council. We received no appropriation to do a long term materials plan. However, the council was established and I understand has begun its work.

The ceramics issue is very, very large. We are not even sure we know everything about it because a great deal of the work we know is going on under classified programs and we stand ready to assist the Critical Materials Council in its work. It has better access to the information and a broader view than we have.

Mr. MCCURDY. Do you believe the Critical Materials Council is the focal point, the managing agency, for R&D in the critical materials area, such as ceramics?

Miss FITZPATRICK. I'm not—I think they are in a better position to get a Government-wide view of what is happening. I'm not sure

they are or should be a managing agency. It may not be useful—the most useful way to approach the problem to simply say we need to coordinate—have a uniform or overall materials research program.

The materials are all being developed for a particular purpose. We all have specifications, things that we want the materials to do. However, there are overlapping areas of interest and we participate in Materials Coordinating Council work. This is aside from the Critical Materials Council. We have an interagency Materials Coordinating Council which meets regularly. We have within the Department of Energy, the various offices working on ceramics and other high temperature materials, a coordinating council.

We try to keep information flowing so that there is not duplication of effort. We try to keep information that is useful to one program available to other programs. I think that system is working pretty well.

Mr. McCURDY. Well, I probably have as many clearances as any member of Congress, sitting on the Intelligence Committee and the R&D Subcommittee in Armed Services and yet—and I've seen a lot of the work in other areas, but I have yet to see any coordination of those efforts. I'm concerned that when we talk about the problems in manufacturing technology, we talk about R&D, but manufacturing technology is research and development. That probably, when I mentioned the word "competitiveness" earlier on, that is probably as central to that as any issue.

I am really concerned that MITI doesn't have that point of view. They don't seem to be disturbed by knowing which agency has which function and they appear to be able to coordinate it better than we do.

I think it's important that we develop this long term program. Are you telling me that we are going to wait for the Critical Materials Council to take that lead?

Miss FITZPATRICK. No. We are developing the materials that we need for the mandate that we have from the Congress and my understanding is that the Critical Materials Council is supposed to look at what people are doing and report on the overall Government-wide efforts in various materials areas, and we are coordinating as we work on materials for our specific needs with other agencies who are also working on materials problems.

Mr. McCURDY. And when do you expect this to be accomplished?

Miss FITZPATRICK. The Critical Materials report? I don't know. I can find out for the record.

Mr. McCURDY. Your long-term program plans?

Miss FITZPATRICK. Our long-term program plan is in place.

Mr. McCURDY. In place.

Miss FITZPATRICK. Yes.

Mr. McCURDY. Is that incorporated just in budget numbers or is that incorporated in a specific document? I'd like to see it.

Miss FITZPATRICK. We have a document and I'd be most happy to supply that to the Subcommittee.

Mr. McCURDY. I would appreciate if you would do that.

[Information to be furnished follows:]

ORNL/TM-8896
Category Distribution
UC-95

METALS AND CERAMICS DIVISION

CERAMIC TECHNOLOGY FOR ADVANCED HEAT ENGINES

PROGRAM PLAN

Date Published - June 1984

Prepared for Office of Vehicle and Engine R&D
Assistant Secretary for Conservation and
Renewable Energy

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. DE-AC05-84OR21400

CREDITS:

Composition and makeup: Debbie LeComte
Editing: Irene Brogden

CONTENTS

1. INTRODUCTION AND SUMMARY 1
1.1 PURPOSE 1
1.2 PLAN DEVELOPMENT STRATEGY 1
1.3 PROGRAM APPROACH, GOAL, AND OBJECTIVES 2

2. BACKGROUND 5
2.1 AUTOMOTIVE PROPULSION OVERVIEW 5
2.2 MATERIALS TECHNOLOGY OVERVIEW 5
2.3 ECONOMIC AND ENERGY-SAVING PAYOFF 6
2.4 INDUSTRY-NEEDS ASSESSMENT 7
2.4.1 Increased Reliability 8
2.4.2 Understanding Critical Materials and Processing Variables 9
2.4.3 R&D and Component Testing Program 9
2.4.4 Ceramic Technology Development Program 10
2.5 THE FEDERAL ROLE 10

3. TECHNICAL PLAN 13
3.1 IMPLEMENTATION STRATEGY 13
3.2 TECHNICAL APPROACH 13
3.3 TECHNICAL TASKS AND WORK BREAKDOWN STRUCTURE 14
3.3.1 Materials and Processing Research 14
3.3.2 Design Methodology Research 16
3.3.3 Data Base and Life Prediction Research 17
3.4 PROGRAM SCHEDULE AND MILESTONES 17

4. MANAGEMENT PLAN 19
4.1 MANAGEMENT STRATEGY, IMPLEMENTATION, AND CONTROL 19
4.2 MANAGEMENT RESPONSIBILITIES 21
4.3 PROGRAM ADVISORY AND CONSULTATIVE GROUPS 21

5. RESOURCE PLAN 23
5.1 RESEARCH COSTS AND FUNDING 23
5.2 RESEARCH FACILITIES AND EQUIPMENT 25

6. PROCUREMENT PLAN 27
6.1 PROCUREMENT PROCEDURES 27
6.2 ASSIGNMENT OF PATENT RIGHTS 28

7. REFERENCES 29

Appendix A: SPECIFIC CERAMIC TECHNOLOGY NEEDED FOR ADVANCED GAS TURBINE AND ADIABATIC DIESEL ENGINES 33

Appendix B: DETAILED RESEARCH PLAN 39

Appendix C: DETAILED RESOURCE REQUIREMENTS BY MAJOR PROGRAM ELEMENTS (PERSON YEARS) 63

LIST OF FIGURES

Figure		Page
1	Abridged program activities flowchart	3
2	Introduction of advanced ceramic technology into engine component development and testing programs	9
3	Relationship of major work elements to ceramic component reliability	14
4	Program activities flowchart	15
5	Joint Department of Energy–National Aeronautics and Space Administration work breakdown structure for research tasks	16
6	Ceramic Technology for Advanced Heat Engines milestone chart	18
7	Department of Energy and National Aeronautics and Space Administration coordinated implementation of Ceramic Technology for Advanced Heat Engines Program	19
8	Overview of Department of Energy, Oak Ridge Operations, and Oak Ridge National Laboratory organizational interfaces	20
B.1	Program elements for the Ceramic Technology for Advanced Heat Engines Program	40
B.2	Subelements of program element 1, materials and processing	41
B.3	Classes of material for the monolithic ceramic subelement of program element 1	41
B.4	Organization example of work tasks for silicon nitride ceramics in monolithic subelement of program element 1	42
B.5	Organization example of work tasks for fiber-SiC composites of SiC matrix class in composite subelement of program element 1	45
B.6	Organization example of work tasks for oxide-base ceramic coatings in thermal and wear coating subelement of program element 1	47

B.7 Organization example of work tasks for joining studies for similar materials in ceramic-to-ceramic joint class of joining subelement of program element 1 49

B.8 Work breakdown structure of program element 2, including three subelements 50

B.9 Organization of work tasks for contact interfaces subelement of program element 2 51

B.10 Five-subelement organization of program element 3, data base and life prediction 54

B.11 Work task organization for three subelements of program element 3 55

B.12 Work task organization for two subelements of program element 3 59

LIST OF TABLES

Table		Page
1	Organizations providing input to the ceramic technology assessment	8
2	Program guidance and coordination plan	22
3	Estimated government and industry funding for ceramic technology research applicable to this program plan	24
4	Projected federal agency funding for ceramic technology applicable to automotive heat engines	25
C.1	Resource requirements for Ceramic Technology for Advanced Heat Engines Program	63

ACKNOWLEDGMENTS

This program plan is a result of the efforts and cooperation of many individuals and organizations who contributed their expertise and perspectives. The initiative and guidance of A. A. Chesnes and R. B. Schulz of the U.S. Department of Energy (DOE) Office of Vehicle and Engine Research and Development in the development of this plan are gratefully acknowledged. The primary authors are A. C. Schaffhauser, V. J. Tennery, and E. L. Long of Oak Ridge National Laboratory, with support from R. Silberglitt and S. Rattien of DHR, Inc., and D. L. Raley and R. L. Rentz of Mueller Associates, Inc.

Valuable input on ceramic technology needs and research plans was provided by the ceramic and heat engine industries, government research laboratories, and the university research community, as acknowledged in this document. Their continued guidance and commitment in reviewing and implementing this plan will be crucial to its success. The cooperation and assistance of National Aeronautics and Space Administration (NASA), Department of Defense, and other DOE offices in coordinating complementary research programs is greatly appreciated. Their cooperation will contribute significantly to the overall effectiveness of these government-sponsored ceramic technology programs. The technical and programmatic expertise of T. J. Miller and H. B. Probst of NASA-Lewis Research Center was particularly beneficial in the cooperative joint technical planning and coordination activities with NASA. E. M. Lenoe and R. N. Katz of the Army Materials and Mechanics Research Center also provided valuable technical input.

1. INTRODUCTION AND SUMMARY

1.1 PURPOSE

This *Ceramic Technology for Advanced Heat Engines Program Plan* was developed with extensive input from industry to define the overall technical content and resource requirements necessary for a comprehensive ceramic research program. The program goal is to develop an industrial technology base capable of providing reliable and cost-effective structural ceramics for application in advanced heat engines.

The plan was developed by Oak Ridge National Laboratory (ORNL) in response to a request from the U.S. Department of Energy (DOE) Office of Vehicle and Engine R&D (OVERD). This office has been and continues to be the major source of government support for research and development (R&D) of advanced propulsion systems for highway vehicles. For all advanced propulsion systems, operation at high temperatures is a key requirement for obtaining substantially improved efficiencies. In particular, the advanced gas turbine and the uncooled (adiabatic) heavy-duty diesel programs require components that must withstand higher temperature combustion environments than can conventional or exotic superalloys. Ceramics have the potential to meet this challenge. Produced from abundant raw materials, ceramics can reduce our dependence on high-cost strategic materials, and the light weight and durability of ceramics improve engine performance and increase engine life.

Significant accomplishments in fabricating ceramic components for both the DOE–National Space and Aeronautics Administration (NASA) and the Department of Defense (DOD) advanced heat engine programs have provided evidence that the operation of ceramic parts in high-temperature engine environments is feasible. However, these programs have also demonstrated that additional research is needed in materials and processing development, design methodology, and data base and life prediction before industry will have a sufficient technology base from which to produce reliable cost-effective ceramic engine components commercially.

Recognizing these important needs, OVERD included funding for a new program initiative in the FY 1983–84 budget requests to Congress entitled Advanced Materials Development. The program objective is to conduct a generic ceramic research effort that supports and parallels existing advanced heat engine programs. The FY 1983 appropriation included limited funding to initiate this program. To ensure meaningful results with a minimum expenditure of government funds, a long-range plan is necessary to identify technology base needs; coordinate activities with other industry, government, and university programs; and develop a multiyear technical and resource agenda. This document describes the results of that planning initiative.

1.2 PLAN DEVELOPMENT STRATEGY

To ensure a cost-effective and results-oriented advanced materials program, the following strategy was used in developing a long-range program plan:

- Technology base needs were assessed through an in-depth survey of the ceramic industry, the heat engine industry, other government laboratories, and universities.
- The economic value of structural ceramics was reviewed, and projections of U.S. and foreign research by ceramic and heat engine industries were analyzed.
- A common work breakdown structure was developed with NASA and coordinated with other government agencies to avoid duplication and to make best use of ongoing ceramic research and engine development programs.
- On the basis of the results of the above efforts, a priority-based catalog of OVERD ceramic technology needs was generated, and industry in-house efforts and capabilities were analyzed.
- A detailed multiyear research plan was developed to meet these needs. The plan indicates the technical objectives and requirements, the research skills required, and the organizations and resources needed to implement the work plan.

1.3 PROGRAM APPROACH, GOAL, AND OBJECTIVES

After extensive consultation with industry and other government agencies, ORNL developed an approach to conducting a ceramic technology research program. The intent is to apply the increasing base of fundamental knowledge and research tools to develop new and improved processes for cost-effective ceramic materials with improved reliability and performance characteristics. These improvements will stem from a better understanding of the critical materials and processing variables and the interactions of the materials with the operating environment. An important approach to cost reduction is to improve the yield of reliable components, that is, to reduce the rejection and failure rates. Therefore, the application of improved techniques for process control, detection of small flaws, and proof testing is important.

An abridged version of this approach is illustrated in Fig. 1. As indicated by the flowchart, the major program areas are materials and processing, data base and life prediction, and design methodology. The interactions between the major ceramic technology program areas and heat engine needs show the continuing role that the ceramic and engine industries must play to ensure that specific program objectives and the program goal are met.

The goal of the Ceramic Technology for Advanced Heat Engines Program is to develop an industrial technology base capable of providing reliable and cost-effective high-temperature ceramic components for application in advanced heat engines.

Specific objectives developed in accordance with the results of the industry needs survey and assessment follow.

- Develop improved and new synthesis and fabrication technology to improve the reliability and performance of monolithic and toughened carbide- and nitride-base ceramics for structural applications.
- Develop technology for the synthesis and fabrication of improved high-temperature-toughened oxide ceramics and coatings primarily for thermal barrier and wear applications.
- Develop the ceramic joining technology base required by industry to design and fabricate reliable ceramic attachments.

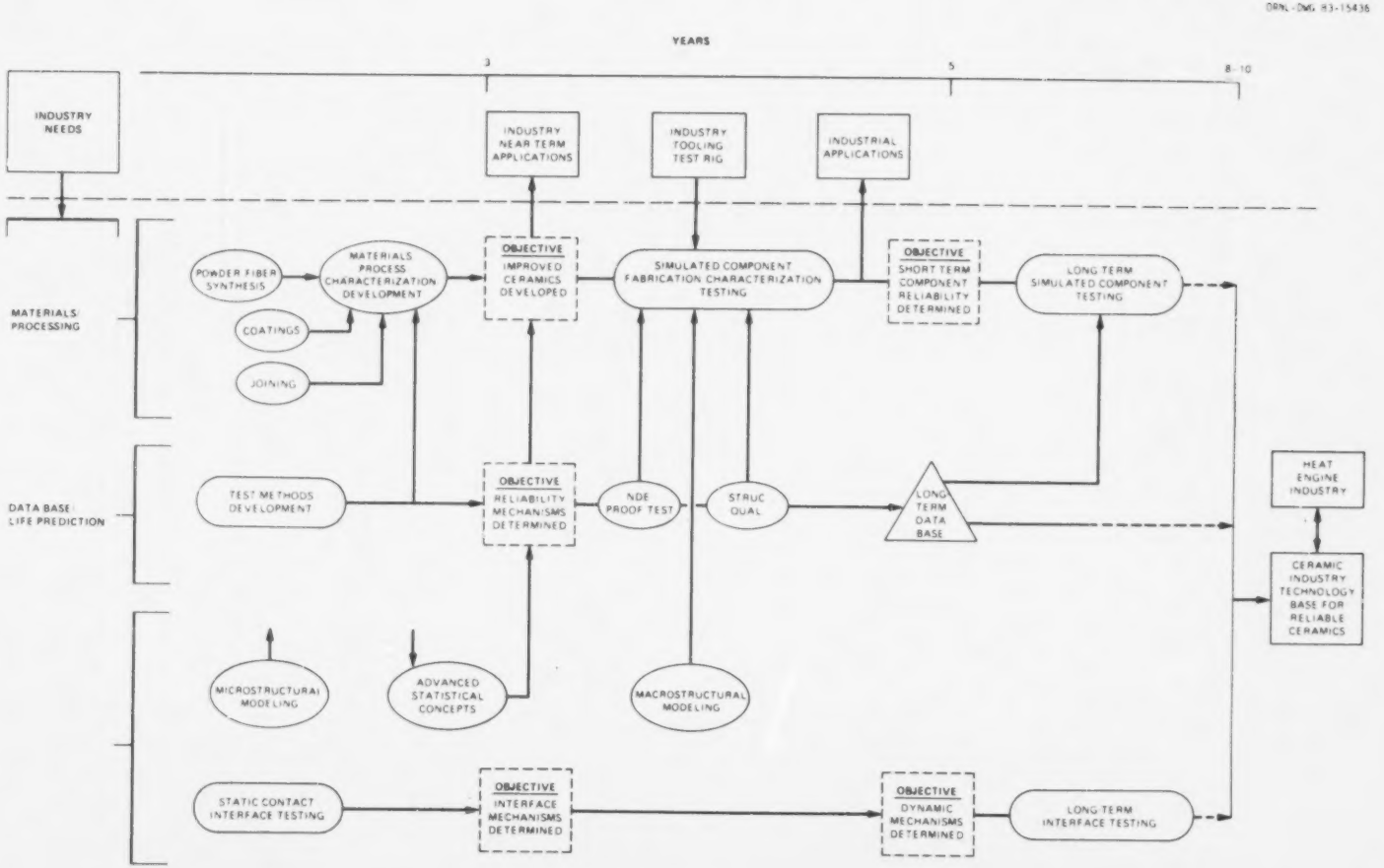

Fig. 1. Abridged program activities flowchart.

4

- Develop the mechanisms controlling those ceramic bulk properties that govern long-term reliability in advanced heat engine environments.
- Determine the mechanisms controlling static and dynamic interface behavior of bulk ceramics and coatings to provide long-term reliability under heat engine conditions.

2. BACKGROUND

2.1 AUTOMOTIVE PROPULSION OVERVIEW

The transportation sector of the American economy depends almost totally on petroleum-base fuels, accounting for 61% of the total petroleum consumed in the United States in 1980 (ref. 1). Highway vehicles accounted for 75% of the transportation petroleum fuels consumed in 1980, and imports of petroleum represented 29% of domestic consumption. The transportation sector's almost total dependence on petroleum contributes heavily to the resulting U.S. need for imported oil. This in turn creates a major adverse impact on the nation's economy through a negative balance of payments (a projected net payment of between $88 and $110 billion will be required in 1990) (ref. 2) and results in an already demonstrated vulnerability to petroleum supply disruptions.

In the long term, based on or paced by market conditions, the ultimate solution to the petroleum problem is the development and implementation of non-petroleum-base fuels. Before and during this development and implementation, primary emphasis will be on developing more fuel-efficient engines and energy conversion systems and on fuel tolerance and adaptability.

The most promising advanced heat engines for highway vehicle propulsion have been identified from research and assessment analyses by industry and government over the past decade. These engine types include the internal continuous combustion gas turbine, the internal intermittent combustion adiabatic diesel, and the external continuous combustion Stirling engine.

In all these advanced engines—in fact, in almost any advanced energy conversion system—overall cycle efficiencies are increased greatly by increased operating temperatures. The realization of these increased efficiencies necessitates the development of materials, such as ceramics, that can withstand the higher operating temperatures.

2.2 MATERIALS TECHNOLOGY OVERVIEW

Materials potentially capable of achieving higher engine operating temperatures include the following:

- advanced metal alloys (made by powder metallurgy, single-crystal, and rapid solidification rate technologies),
- carbon and carbon composites, and
- structural ceramics (monolithics, composites, and coatings).

Of these, the first two are being developed by either industry or the military. However, most advanced metal alloys do not actually offer a practical low-cost high-temperature capability, and carbon and carbon composites are quite expensive and oxidize in air at high temperatures. Structural ceramics have great potential for enabling the cost-effective high-temperature operation of engines but require substantial development.

As a class, ceramic materials are hard and brittle as well as heat and corrosion resistant. Many ceramics can perform effectively at temperatures considerably higher than can specially developed metal alloys, but ceramics exhibit brittle fracture. This latter characteristic, a key difference between ceramic materials and metal alloys, is the major impediment to the widespread use of ceramics as engineering structural materials. The ceramic materials of principal interest for applications in advanced heat engines include silicon carbide (SiC), silicon nitride (Si_3N_4), zirconia (ZrO_2), aluminum oxide (Al_2O_3), and a variety of other oxides and silicates. Generally, these pure materials are alloyed with other ceramics (or metals) for sintering and toughening or for other modifications. These ceramics are fabricated into desired shapes from fine powders and are subsequently densified into useful products by exposing the fabricated shapes to high temperatures in a suitable atmosphere. This procedure results in many properties of a ceramic material depending more strongly on the manufacturing process than do products made of metallic alloys. For example, the major variables that determine the properties of ceramics include the particle size, shape, and surface chemistry of the powders; the chemical impurities in the powders; the procedures and additives employed to shape the green-state (prefired) parts; the time-temperature-atmosphere combination used to densify the part; and any postdensification processing (e.g., machining of the surface). Also, the interaction of the operating environment with flaws and impurities in the ceramics can reduce their long-term reliability.

In recent years, industry's improved knowledge of the behavior of ceramics and its improved control over the fabrication process have led to the use of ceramics in increasingly difficult and specialized applications. One example is an electrically insulating substrate for electronic devices such as large-scale integrated circuits. A major new application—the focus of this plan—is the use of high-performance structural ceramics as components in heat engines.

The potential of ceramics for heat engine applications has been proved by government and industry engine and component R&D programs. The program outlined in this plan is designed to determine the mechanisms governing the processing and properties of ceramic materials, to develop the techniques to control the critical variables required to improve reliability, and thereby to develop the industrial technology base required.

2.3 ECONOMIC AND ENERGY-SAVING PAYOFF

The energy-saving potential of ceramics in automotive propulsion systems is based, first, on higher operating temperatures and, second, on reduced friction, weight, and inertia stemming from the mechanical and physical properties of ceramics. Various proof-of-concept engine development programs sponsored by DOE and DOD (the General Motors AGT-100, the Garrett/Ford AGT-101, and the Cummins Adiabatic Diesel programs) forecast potential efficiency improvements from 30 to 50% over today's technology.

Ceramics will most likely enter the highway vehicle marketplace incrementally; therefore, their full energy-saving potential will not be realized immediately. Nevertheless, a first-order estimate, based on a conservative 20% fuel efficiency improvement, can result in an annual highway vehicle fuel use savings of up to several exajoules (quads) after ceramics are fully applied to the vehicle fleet. At today's crude oil prices, assuming that the savings would result in reduced imports, the annual reduction in the balance-of-trade deficit would be about $15 billion. Even with a gradual buildup in the use of ceramics over a 15-year period beginning in 1990, the annual savings in early years would still be from one to several billion dollars.

Argonne National Laboratory (ANL) recently undertook a detailed economic analysis of the importance of ceramics to the U.S. economy. Its preliminary analysis estimated the market size and level of penetration of ceramics in various applications in several time frames and for a full range of applications.[3] Comparing a business-as-usual approach with one based on an aggressive pursuit of advanced ceramics (by U.S. and foreign interests), the annual value of the U.S. ceramic market in the year 2000 would range from about $500 million to $3 billion. The study then noted that "significantly different benefits could be expected depending upon whether the U.S. or foreign countries reach the marketplace initially." Two scenarios were drawn, one a "U.S. Dominant Case" and the other the "Foreign Dominance Case." Using the Data Resources, Inc., long-term outlook of the U.S. economy and addressing only the heat engine market, the report indicated that the U.S. Dominant Case relative to the Base Case shows an annual real gross national product some $2.5 billion higher in 1990, rising to $15.2 billion in 1995 and to $28.2 billion in 2000, with a narrowing thereafter. The report states further,

> Between 1985 and 2005, the cumulative real GNP gain (U.S. Dominant Case over Base Case) is $278.9 billion (1981 $). As can be observed, the contribution of ceramic technology is potentially enormous, even when the future gains are discounted to allow for inflation. Similarly, when the "Base Case" is compared to the "Foreign Dominance Case" annual GNP goes down by $0.2 billion in 1985, by $2.2 billion in 1990, by $11.1 billion in 1995 and by $6.5 billion in 2000, with the cumulative real GNP loss between 1985 and 2005 estimated to be $110.7 billion (1981 $).

In essence, the ANL report projects that the potential difference in American benefits between U.S. and foreign dominance can be about $400 billion in discounted 1981 dollars, with a positive potential for 250,000 new U.S. jobs by the year 2000.

2.4 INDUSTRY-NEEDS ASSESSMENT

The industry-needs assessment was conducted to obtain the information required to develop a program plan consistent with industry requirements. The assessment was focused on critical technology needs for ceramics in advanced gas turbines and adiabatic diesel engines. The relationship of ceramics technology to other engine concepts and other applications such as off-road equipment, military vehicles, stationary engines, and cogeneration systems was also considered.

The strategy for this assessment was to determine the critical technology needs for ceramics for advanced heat engine applications, to identify the potential technology areas requiring government funding, and to review the current programs and plans of other federal agencies for ceramic technology in order to avoid unnecessary duplication. The approach was to review the status of current heat engine ceramic programs thoroughly[4–5] and to obtain direct input from site visits and other contacts with major engine manufacturers, ceramic manufacturers, industrial laboratories, government laboratories, and universities. The organizations visited or directly contacted are listed in Table 1.

The following discussion summarizes the generalized findings from the industry-needs assessment. Specific ceramic technology needs and technical requirements identified by industry for the advanced gas turbine and adiabatic diesel engines are presented as Appendix A.

Table 1. Organizations providing input to the ceramic technology assessment

Organization category	Organization providing input
Ceramic industry	AiResearch Casting, Carborundum, Coors, Corning Glass, Dow-Corning, General Electric, GTE, Norton
Engine manufacturers	Caterpillar, Cummins, Detroit Diesel Allison, Ford, Garrett Turbine Engine, Solar Turbine, Rocketdyne
Industrial laboratories	Battelle Columbus, Babcock and Wilcox, General Electric, Rockwell, Westinghouse, United Technologies
Government laboratories	AFML, AMMRC, ANL, JPL, LANL, LBL, NRL, NASA-LeRC, NBS, ORNL, PNL[a]
Universities	Alfred, Berkeley, Florida, Georgia Tech, Illinois, MIT, Michigan, NC State, Ohio State, Penn State, Rutgers, Washington
Other government offices and agencies	DOE: ER, FE, AES, IP; DOD: DARPA, ONR, TACOM; NASA-OSTP; NSF[b]

[a]Air Force Materials Laboratory, Army Materials and Mechanics Research Center, Argonne National Laboratory, Jet Propulsion Laboratory, Los Alamos National Laboratory, Lawrence Berkeley Laboratory, Naval Research Laboratory, National Aeronautics and Space Administration-Lewis Research Center, National Bureau of Standards, Oak Ridge National Laboratory, Pacific Northwest Laboratory.

[b]U.S. Department of Energy: Energy Research, Fossil Energy, Advanced Energy Systems, Industrial Programs; U.S. Department of Defense: Defense Advanced Research Project Agency, Office of Naval Research, Tank Automotive Command; National Aeronautics and Space Administration-Office of Scientific and Technical Projects; National Science Foundation.

2.4.1 Increased Reliability

Increased reliability of ceramics is the major technology needed. The major technology needed for ceramics for advanced heat engines is to increase the reliability of current materials and to investigate new materials and processes having the potential for higher reliability. Although significant progress has been made to improve the short-term properties of some currently used materials and components, greater reproducibility is required, and there are very few data on long-term properties in the heat engine environments. This raises serious concern about long-term reliability.[6] The currently used materials (SiC, Si_3N_4, and ZrO_2) have variable properties and limited strength margins. The properties will likely degrade with time under the severe temperature and cyclic operating conditions typical of those found in advanced heat engine applications. Although gross flaws can usually be detected, it is extremely difficult to identify or even to detect the small (10- to 50-μm) strength-limiting flaws in good-quality components by use of current nondestructive evaluation (NDE) techniques. The very sophisticated NDE techniques being developed for research will probably be too costly for use in the routine manufacturing of complex shapes; thus, most of this NDE effort should be focused on in-process control.

One of the thrusts of the development of ceramic materials should be an increase in their fracture toughness to obtain higher strength margins and to reduce their susceptibility to flaws and environmental degradation. Ceramic matrix composites promise greater toughness and include transformation- and dispersion-toughened ceramics and ceramic whisker-, short fiber-, and continuous-fiber-reinforced ceramic materials.[7] These new materials and their requisite processing techniques must be amenable to cost-effective near-net-shape fabrication methods for automotive applications.

Table 1. Organizations providing input to the ceramic technology assessment

Organization category	Organization providing input
Ceramic industry	AiResearch Casting, Carborundum, Coors, Corning Glass, Dow-Corning, General Electric, GTE, Norton
Engine manufacturers	Caterpillar, Cummins, Detroit Diesel Allison, Ford, Garrett Turbine Engine, Solar Turbine, Rocketdyne
Industrial laboratories	Battelle Columbus, Babcock and Wilcox, General Electric, Rockwell, Westinghouse, United Technologies
Government laboratories	AFML, AMMRC, ANL, JPL, LANL, LBL, NRL, NASA-LeRC, NBS, ORNL, PNL[a]
Universities	Alfred, Berkeley, Florida, Georgia Tech, Illinois, MIT, Michigan, NC State, Ohio State, Penn State, Rutgers, Washington
Other government offices and agencies	DOE: ER, FE, AES, IP; DOD: DARPA, ONR, TACOM; NASA-OSTP; NSF[b]

[a]Air Force Materials Laboratory, Army Materials and Mechanics Research Center, Argonne National Laboratory, Jet Propulsion Laboratory, Los Alamos National Laboratory, Lawrence Berkeley Laboratory, Naval Research Laboratory, National Aeronautics and Space Administration-Lewis Research Center, National Bureau of Standards, Oak Ridge National Laboratory, Pacific Northwest Laboratory.

[b]U.S. Department of Energy: Energy Research, Fossil Energy, Advanced Energy Systems, Industrial Programs; U.S. Department of Defense: Defense Advanced Research Project Agency, Office of Naval Research, Tank Automotive Command; National Aeronautics and Space Administration-Office of Scientific and Technical Projects; National Science Foundation.

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2.4.4 Ceramic Technology Development Program

An effective ceramic technology development program requires a well-planned and well-coordinated industry, government, and university effort with a multiyear funding commitment. Although the engine manufacturers and ceramic companies are encouraged by successes to date in showing the feasibility of designing and fabricating ceramic components for advanced heat engines, the technology and applications are still considered to be of very high risk and long term by industry management. Because of the risk, high development costs, and long development time required before the technology would be ready for the marketplace, it is unlikely that industry would continue this development work without significant government support. However, because the potential payoff is high, industry has been willing to share costs with the government and to commit high-quality personnel to the programs. To involve industry effectively and to secure its maximum contribution, the government needs to make a commitment to stable long-term funding (five to ten years) to develop the technology to the stage that industry can justify the large tooling and manufacturing costs required to commercialize this technology. To encourage industry participation and cost sharing, its patent and proprietary information rights must be protected. Consequently, a more cooperative policy between government and industry is required to promote joint industry programs and licensing agreements.

Industry recognizes the significant R&D support role that can be provided by government laboratories and universities. During the past few years, a variety of new materials-analysis techniques have been developed, which can potentially provide chemical and microstructural details critical to the properties of structural ceramics. These techniques are highly specialized, and the required equipment is unique and expensive. Few, if any, of the current ceramic suppliers for the heat engine programs have had the capital or incentive to apply these techniques to their materials. Many of the facilities required to apply these new techniques exist at government laboratories and universities. The unique research facilities and expertise of these organizations should be used to help industry meet this difficult technological challenge.

2.5 THE FEDERAL ROLE

Depressed economic conditions affecting domestic automotive companies have resulted in declining corporate ability to fund long-term R&D adequately unless supported by the federal government. A further complication for ceramic research, and one that significantly constrains the automotive industry's interest at this time, is that the performance characteristics of ceramics differ so markedly from those of metals now used in engines. The long-term application of ceramic components will necessitate major expenditures in engine redesign. Specifically, although ceramics have major potential advantages in high-temperature strength and corrosion resistance, their brittleness creates new problems for engine design, particularly the avoidance of stress concentrations leading to fracture. As a result, the extensive use of ceramics will require a long period of both ceramic R&D and engine development. It is this latter commitment that engine manufacturers are reluctant to make until a sound industrial ceramic technology base is in place to guarantee reliable component availability.

At the same time, the ceramic industry in general is too small and has too little capital to perform the high-risk R&D for which there is no assurance of near-term business success. Research has not yet progressed to the point that one or more ceramic materials or fabrication techniques

stand out as being clearly superior for any particular heat engine application. Federally supported research to date has catalyzed parallel industry research, and the current government-funded advanced engine development programs and supporting material research programs have provided a focus and integration of limited capabilities and resources, which has resulted in significant technical progress and accomplishment.

Countries such as Japan and several European nations have also realized the potential value of ceramics for heat engine applications and are moving forward aggressively. Japan's interest in ceramics has accelerated to the point that U.S. experts believe that the Japanese technology is now equal to, or in some cases superior to, that of the United States. The Japanese Ministry of International Trade and Industry (MITI) has made a national commitment to a major ten-year coordinated government, university, and industry program to exploit the potential of ceramics in heat engines. The strong interest in Europe is evidenced by government-supported programs in Germany, France, Italy, and Sweden.

In summary, both the ceramic industry and the engine and vehicle industry recognize the potential of ceramics and are expending considerable corporate resources to upgrade their technology. However, because of the long-term high-risk nature of the work, it will be virtually impossible for industry to develop the extensive technology base required for application of reliable ceramics to major heat engine developments without significant government support. In addition, factors such as the high-risk high-payoff nature of the research; the national energy and economic benefits; the need for coordinated federal agency, institutional, and private sector efforts; and international governments' emphasis in the area, combined with the positive impact on national strategic materials requirements, all strengthen the requirement for a strong federal role.

3. TECHNICAL PLAN

3.1 IMPLEMENTATION STRATEGY

The foundation of program implementation is the heavy emphasis on industry's involvement, not only in technology efforts themselves but also in providing continuous input to federal program direction and priorities and in evaluating program progress. The program will focus on the long-term high-risk R&D areas identified by industry. The mechanism for linking basic research results to practical applications will be developed through an effective feedback loop between the R&D tasks and the component tests in realistic engine environments. This feedback loop was illustrated in Fig. 2. Potential improvements in materials and processing, design methodology, and life prediction must be applied to simulated or actual engine components tested in realistic engine environments to confirm that the required improvements are achieved and to identify those areas requiring additional improvement. The current government and industry advanced engine programs have developed the required test facilities and are currently determining the limitations of components fabricated with existing materials and processes. Feedback from these tests is critical to providing direction to the R&D program now and during future implementation.

3.2 TECHNICAL APPROACH

The interaction between the three major elements of the technical approach and the necessary operations of materials characterization, component fabrication, and component testing to achieve the program goal and objectives is shown in Fig. 3. As shown in the figure, the technical approach includes research in the three areas crucial to the development of reliable ceramic components: materials and processing, design methodology, and data base and life prediction. These research areas from the major work elements of the work breakdown structure are discussed in Sect. 3.3.

The overall approach to the ceramic technology for advanced heat engines is illustrated in the program flowchart (Fig. 4). In addition to illustrating the major work elements and their interactions, the flowchart indicates the relative timing of events and examples of inputs and outputs required and anticipated during the program. Some major objectives and milestones are also included to provide a measure of expected relative progress as the program proceeds. Specific ceramic technical needs and objectives obtained from industry for advanced gas turbines and adiabatic diesel engines are provided in Appendix A.

The program builds on the advances made in the heat engine component and system development programs. The program also uses concepts and research tools developed in more basic (fundamental) ceramic research programs, primarily at universities and government laboratories. For example, the program will use the latest materials analysis techniques capable of providing chemical and microstructural details critical to property, processing, and performance relationship determinations. Use of industry's existing component tooling and testing rigs is another cost-effective part of the technical approach.

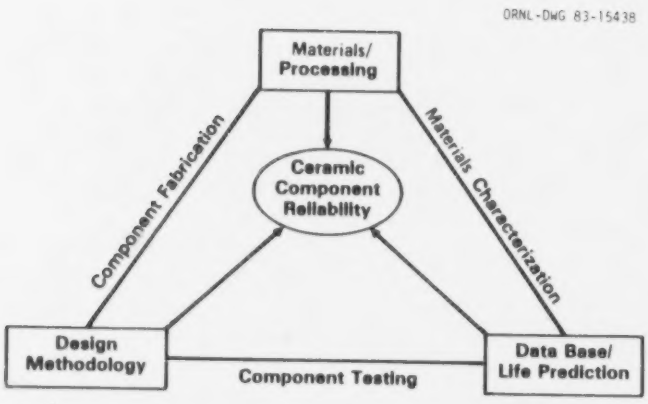

Fig. 3. Relationship of major work elements to ceramic component reliability.

Note that the activities under these work elements represent a priority-based approach to satisfying the needs of industry. These activities are considered necessary to realize the goal of reliable cost-effective high-temperature ceramics for advanced heat engine applications. As will be discussed in Sect. 4, a mechanism will be in place (Program Advisory Consultative and Technical Task groups) to facilitate changes in the program's research needs and objectives should this become necessary during the research program.

3.3 TECHNICAL TASKS AND WORK BREAKDOWN STRUCTURE

The technical tasks required to meet industry's needs have been organized within the program's work breakdown structure. Materials and processing is the primary program work element. The data base and life prediction and the design methodology work elements complement and support the materials and processing activities by establishing a long-term testing data base. Subcategories of research within each of the three major work elements are identified in the work breakdown structure, shown in Fig. 5. The work breakdown structure was developed jointly by ORNL and NASA-Lewis Research Center (LeRC) to facilitate coordination of complementary tasks funded by DOE, NASA, other government agencies, and industry. Detailed descriptions of the technical needs, approach, and goals of research under each of the subelements and tasks of the work breakdown structure are presented in Appendix B and are summarized in the following discussion.

3.3.1 Materials and Processing Research

The objective of the materials and processing research is to develop processing methods that can yield materials with the uniform microstructures and high-temperature mechanical and corrosion-resistant properties required of advanced engine components. Principal research areas include powder synthesis and characterization (to increase uniformity and controllability of properties); processing, characterization, and densification of green-state ceramics (to understand how to improve the densified material through adjustments in green-state processing or in the densification process itself); and structural, mechanical, and physical properties of dense ceramics (to facilitate determination of critical materials, processing, and property correlations). Materials to be studied include

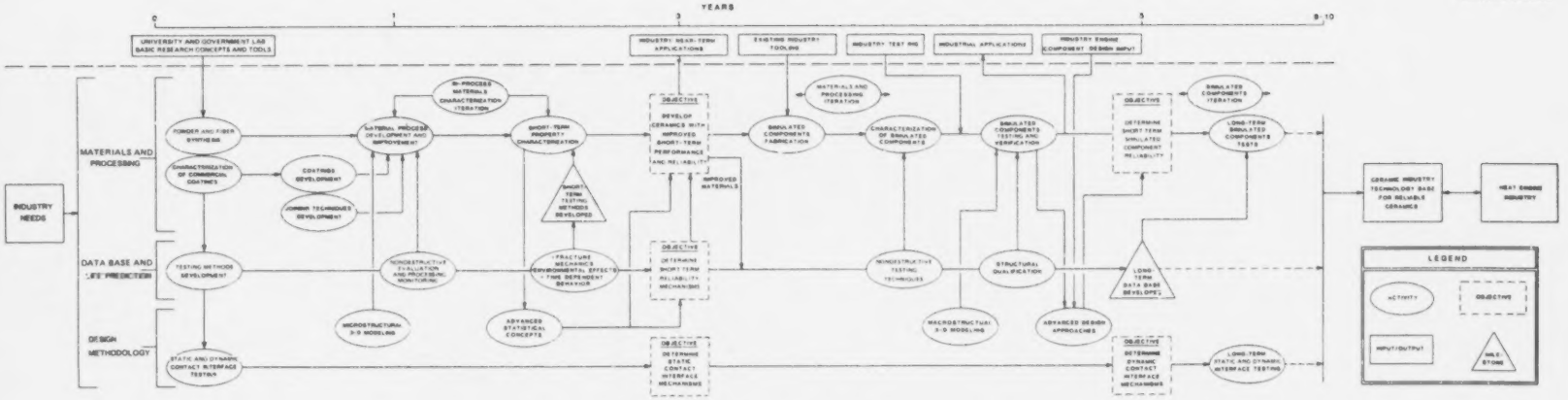

Fig. 4. Program activities flowchart.

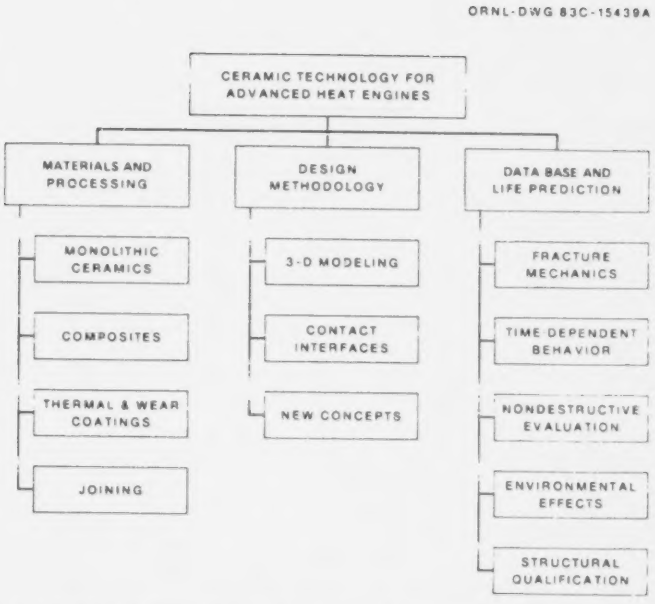

Fig. 5. Joint Department of Energy–National Aeronautics and Space Administration work breakdown structure for research tasks.

monolithic SiC, Si_3N_4, silicates, sialons, dispersion- and transformation-toughened composites with matrices of all the above materials, and oxide composites. The research will complement that being pursued by industry and other government programs. For example, DOD has initiated a major thrust on the synthesis of long fibers from polymer precursors and the development of fiber-reinforced SiC and Si_3N_4 composites from these fibers. The DOE program will complement DOD's thrust by use of these fibers to toughen oxide and silicate matrix composites. Research on coatings will address the lack of fundamental understanding in this area to allow the development of reliable methods for applying and characterizing coatings and for developing improved coating materials. Research on joining includes development of advanced joining processes and the physical, structural, and mechanical properties of ceramic-to-metal and ceramic-to-ceramic joints. Emphasis is on developing a sound technology base for producing permanent joints having acceptable properties for structures of interest in advanced engines.

3.3.2 Design Methodology Research

Research in design methodology is oriented to understanding the properties of brittle ceramics under stress well enough to predict their lifetime in specific engine component uses accurately. The research involves finite-element modeling on a microscopic scale, studying static and moving interfaces between ceramics and other ceramics or selected metal alloys, and developing and utilizing advanced statistical representations for new design methodologies tailored to the use of ceramics in advanced heat engines.

3.3.3 Data Base and Life Prediction Research

Research efforts in the data base and life prediction area are focused on developing techniques, generating concepts, and acquiring data on both existing and improved ceramic materials necessary to improve mechanical and environmental reliability. These efforts encompass structural qualification procedures and testing for ceramic engine components, making full use of available industrial testing rigs for both turbine and diesel engines; detailed study of time-dependent and environmental effects in simulated service environments (in particular, characterization of the long-term behavior of both existing and improved materials); and development of advanced NDE methods that can be used in combination with design methodology to generate accurate service life predictions. The key research issues are to verify that the critical flaws can be detected for complex shapes and that the proof-testing methods are applicable to components subjected to the combined stresses of the engine environment for extended periods. The major failing of present NDE techniques is that they cannot detect the very small (10- to 50-μm) inherent flaws that lead to catastrophic failure in ceramic components. New, more sensitive techniques need to be developed to allow both reliable component lifetime predictions and highly sensitive quality control of materials processing itself (e.g., size and location of inhomogeneities in green-state materials).

3.4 PROGRAM SCHEDULE AND MILESTONES

A generalized schedule and milestone chart (Fig. 6) has been developed for the orderly accomplishment of the tasks identified in the work breakdown structure. In addition to milestones, the chart also indicates relationships between elements as appropriate. Although the program is forecast to be a long-term effort (as indicated in Fig. 3), milestones have been established for the first five years only. As the program is conducted, results of scheduled periodic reviews will naturally change certain milestones and add new ones.

In general, the horizontal lines represent activities conducted in-house by DOE, by other government agencies, and by industries and institutions under contract to these agencies. The initiation milestones reflect the anticipated timing for issuing requests for proposals (RFPs) for contracts in the area indicated.

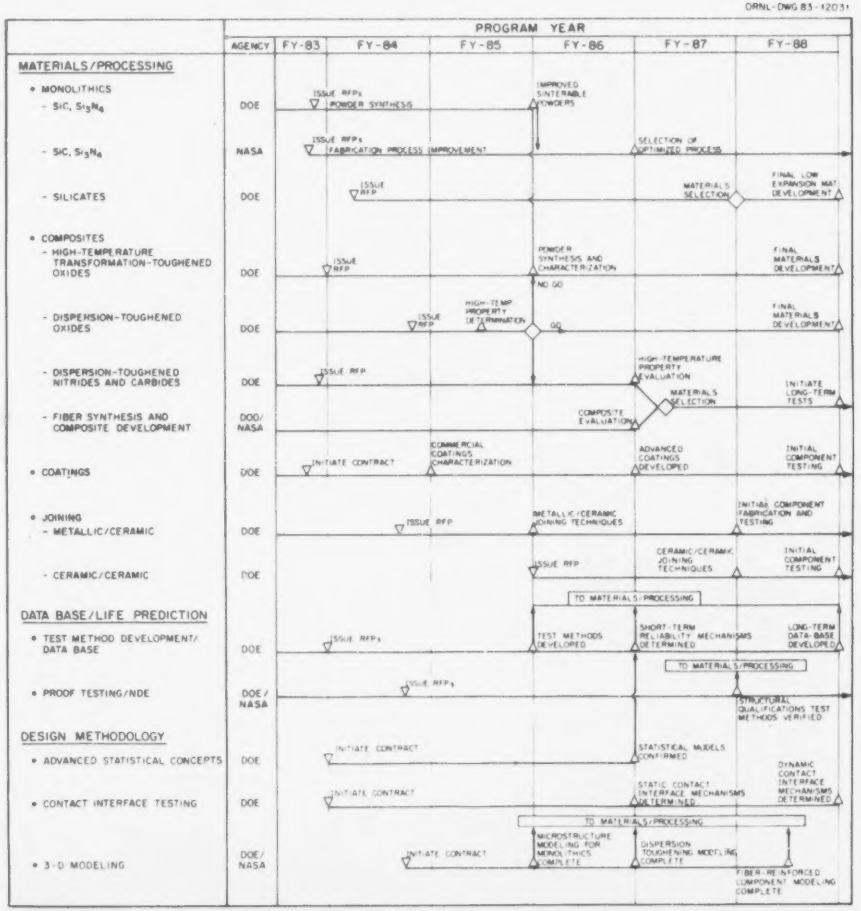

Fig. 6. Ceramic Technology for Advanced Heat Engines milestone chart. RFPs, requests for proposal.

4. MANAGEMENT PLAN

4.1 MANAGEMENT STRATEGY, IMPLEMENTATION, AND CONTROL

The Office of Vehicle and Engine R&D (OVERD), under the Assistant Secretary for Conservation and Renewable Energy, is responsible for managing this program and the advanced automotive heat engine programs. The DOE is responsible for establishing the program goal and objectives, implementation policies, and funding levels. It is also responsible for coordination with other federal agencies and DOE offices. Figure 7 shows the very close coordination of program planning and budgeting with NASA and DOD on this program and the engine development programs.

In accordance with the DOE policy of decentralizing project management to field and laboratory sites with established capabilities, DOE-OVERD is assigning responsibility for the day-to-day management of the Ceramic Technology for Advanced Heat Engines Program to the Oak Ridge Operations Office (ORO) as the principal field office and to ORNL as the lead national laboratory. The project management responsibilities of ORNL include technical project planning, implementation, and control. Joint technical planning and coordination of this program with the complementary NASA ceramic technology program for aerospace engine applications is managed by NASA-LeRC. Coordination and joint funding of some technical tasks with DOD are accomplished through a DOE interagency agreement between OVERD and the DOD Army Materials and Mechanics Research Center (AMMRC).

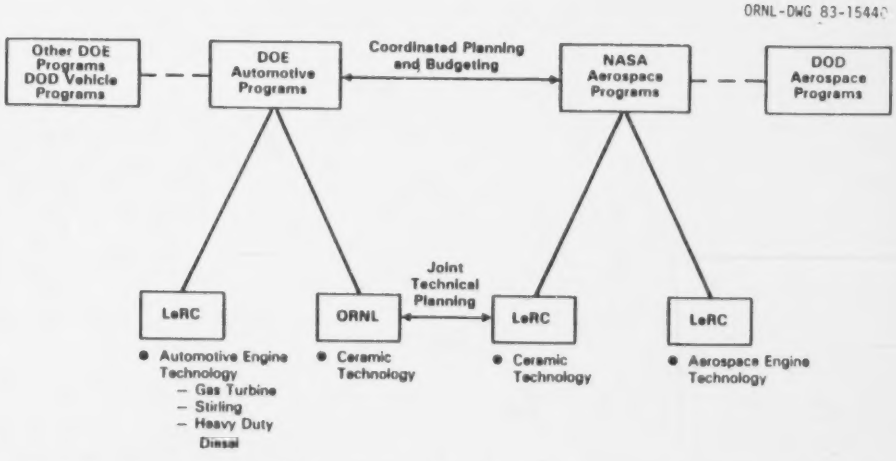

Fig. 7. Department of Energy and National Aeronautics and Space Administration coordinated implementation of Ceramic Technology for Advanced Heat Engines Program.

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This program will be managed in accordance with a management plan prepared by ORNL and approved by OVERD. The management plan shall specify the OVERD, ORO, and ORNL organizational interfaces, responsibilities, program implementation and procurement policies, and management controls. The DOE, ORO, and ORNL organizational interfaces are shown in Fig. 8. The formal program direction and budget guidance are provided to ORO by OVERD through program guidance letters. The ORO is responsible for managing the prime contract, currently with Martin Mariette Energy Systems, Inc., for the operation of ORNL.

The management controls for this program include financial and technical progress reports and periodic program review and coordination meetings. Bimonthly project review meetings of ORO, ORNL, and DOE will be conducted. Bimonthly management reports will provide technical highlights and details of the financial, procurement, and milestone status of all in-house and subcontractor work. Semiannual technical progress reports, topical reports, and open literature publications on appropriate completed work will be issued. Management and technical coordination issues will be presented to the DOE advisory committee for this program (see Sect. 4.3). The DOE-NASA bimonthly management meetings, technical progress, and coordination items will also be presented as appropriate and/or at the annual meetings of the DOE Energy Materials Coordinating Committee, the Interagency Working Group on Ceramics for Heat Engines, and the DOE-OVERD Contractor Coordination meetings.

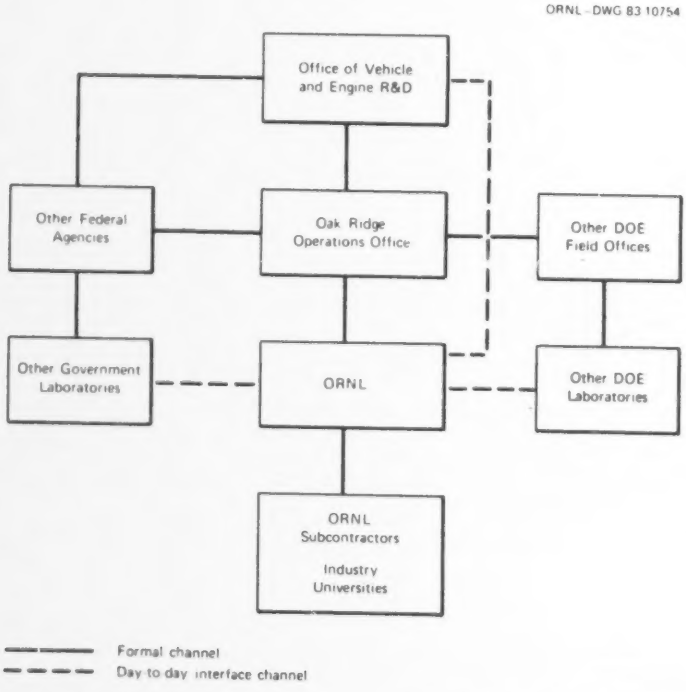

Fig. 8. Overview of Department of Energy, Oak Ridge Operations, and Oak Ridge National Laboratory organizational interfaces.

The ORNL is responsible for implementing the program, with program direction and budget guidance from OVERD through ORO. A program implementation plan will be prepared annually by ORNL in the form of a field task proposal/agreement (a three-year annual operating plan) for approval by DOE. These plans include detailed cost projections, funding distribution, milestones, and technical descriptions of all in-house and subcontract tasks.

4.2 MANAGEMENT RESPONSIBILITIES

Management of the Ceramic Technology for Advanced Heat Engines Program must direct the required R&D activities of the effort throughout the program; these activities must be responsive to the needs identified by industry. A proper mechanism must be in place to ensure the incorporation of changing or additional industry needs as they occur (see Sect. 4.3). Generically, the assigned management responsibilities address the following elements:

- accomplishment assessments,
- iterative refinement of work activity based on industry review and oversight,
- technology assessment,
- identification of unknowns,
- determination of relevant activities,
- schedule priorities,
- conduct of work, and
- report on work.

The management plan to be prepared by ORNL will address these elements.

4.3 PROGRAM ADVISORY AND CONSULTATIVE GROUPS

The new and existing committees and working groups involved in guiding and coordinating this program are listed in Table 2. The DOE will establish a new industry-university advisory committee to provide overall guidance on program objectives and priorities. Technical task groups for the major program elements will be established by ORNL for technical planning, coordination, and review. The membership of each task group will include the appropriate program participants and technical representatives from interfacing DOE, DOD, NASA, and industry programs. Other existing organizations, including the DOE Energy Materials Coordinating Committee, the Interagency Working Group on Ceramics for Heat Engines, and the International Energy Agency, will be employed to promote coordination and information exchange.

Table 2. Program guidance and coordination plan

New or existing organizations	Purpose	Membership[a]
Advisory committee to DOE	Recommend objectives, goals, and priorities	Industry, universities, government (nonvoting)
Technical task groups—materials processing, design methodology, data base and life prediction	Provide technical planning, coordination, and review	Program participants and representatives from NASA, DOD, and other DOE programs and other industries
Energy Materials Coordinating Committee	Coordinate structural ceramic research at DOE	Energy Research, Fossil Energy, Conservation and Renewable Energy, and Nuclear Energy
Interagency Working Group on Ceramics for Heat Engines	Project information exchange and coordination	DOE, DOD, NASA, and National Bureau of Standards
International Energy Agency	Balance technical information exchange	West Germany and possibly Japan

[a]DOD, U.S. Department of Defense; DOE, U.S. Department of Energy; NASA, National Aeronautics and Space Administration.

5. RESOURCE PLAN

5.1 RESEARCH COSTS AND FUNDING

The resources required to meet the objectives and goals of this program are substantial. To complete the technical tasks in the work breakdown structure detailed in Appendix B, an estimated average of almost 200 person-years per year (PY/Y) of research and technical support personnel over a five-year period is required. (The detailed allocation of resources by work element to accomplish the entire work breakdown structure is given in Appendix C.) At the current average cost of $120,000/PY for research labor, overhead, and material costs, the five-year research program cost would be $140 million (assuming a 6% per year cost escalation and $8 million for program management costs). Although this expenditure is small compared with the potential economic benefits, it is a significant cost if totally funded by an industry or by a single government agency for a specific application. Fortunately, much of the technology is generic and is applicable to a range of automotive, aerospace, military, and industrial requirements. Therefore, the OVERD funding for this program considers the contributions from other DOE-, federal agency-, and industry-funded programs in accomplishing the goals of this plan.

Estimated portions of the continuing and new FY 1983–84 ceramic research programs funded by DOE, DOD, NASA, National Science Foundation (NSF), and industry applicable to automotive heat engines and the tasks in the work breakdown structure are given in Table 3. Because of the importance of ceramics, DOE, DOD, and NASA funded new initiatives on ceramic research in FY 1983. These new initiatives include $2 million from DOE Advanced Materials Development (first year of this plan), $3 million from DOE Ceramic Fiber Composites, and $2.5 million from NASA Ceramic Technology for Aerospace Heat Engines. The NASA research budget for Ceramic Technology for Aerospace Heat Engines shown in Table 3 represents 90% of its ceramic technology program, because most of the program is applicable to automotive heat engines. For the DOD Ceramic Composite Program, 50% of the funding for fiber composite research is included in the program plan (fiber process development and manufacturing technology for fiber production were not included). For other government programs listed, about 50% of the funding was estimated to be applicable to this plan. Industry is also increasing its research funding on ceramics through cost sharing in the new initiatives and additional research tasks within the companies and at universities. Although most of the current industry funding is focused on developing near-term products and component fabrication capability, some of the more basic industry research and most of the new cost-shared and industry-sponsored university research is applicable to this program.

The estimated total resources required (Table 4) are based on a full-scale effort on the priority research needs detailed in this plan without consideration of either unexpected breakthroughs or funding limitations that might result in a slower paced program. It should be recognized that these resource estimates are for planning only. Future DOE funding requests will depend on the availability of government funding, the priority of this effort compared with other national needs, the time phasing of activities, and modifications in funding plans by other government agencies or industry.

Table 3. Estimated government and industry funding for ceramic technology research applicable to this program plan

Funding source	Estimated funding ($ million)[a]	
	FY 1983	FY 1984[b]
Department of Energy (DOE)		
Ceramic Technology for Advanced Heat Engines[c]	2.7	4.6
Energy Conversion and Utilization Technologies	0.6	0.6
Fossil Energy	1.0	1.0
Basic Energy Sciences	1.0	1.0
Total DOE	5.3	7.5
National Aeronautics and Space Administration (NASA)		
Ceramic Technology for Aerospace Heat Engines[d]	3.0	4.0
University grants	0.3	0.3
Total NASA	3.3	4.3
U.S. Department of Defense (DOD)		
Defense Advanced Research Projects Agency Ceramic Fiber Composite Program	0.5	2.5
Air Force, Army, and Navy research and technology[d]	2.0	2.5
Total DOD	2.5	5.0
National Science Foundation (NSF)		
University grants—total	0.5	0.5
Industry		
Cost sharing on government contracts	0.4	0.8
Company basic research	2.8	4.7
University grants	0.7	1.0
Total industry	3.9	6.5
Total funding	15.5	23.8

[a]Budget authority for research and technical support personnel including overhead and materials but excluding direct program management cost.

[b]Based on congressional appropriations and estimated industry funding.

[c]Includes funding for Advanced Materials Development and applicable portion of Vehicle Propulsion research and development funding.

[d]Includes estimated funding for government employees performing research at NASA and DOD laboratories.

Table 4. Projected federal agency funding for ceramic technology applicable to automotive heat engines

	Estimated funding ($ millions)					
	Fiscal year					Five-year total
	1985	1986	1987	1988	1989	
Department of Energy (DOE) Ceramic Technology for Automotive Heat Engines	6.3	10.6	14.9	16.9	10.5	59.2
Other DOE programs	3.0	3.0	3.0	3.0	3.0	15.0
National Aeronautics and Space Administration (NASA) Ceramic Technology for Aerospace Heat Engines[a]	5.0	6.0	7.0	8.0	9.0	35.0
Department of Defense (DOD)–Defense Advanced Research Project Agency (DARPA) Ceramic Fiber Composites Program	2.5	4.0	5.0	1.0	0	12.5
DOD Army, Navy, and Air Force research and technology[a]	4.0	4.0	4.0	5.0	5.0	22.0
National Science Foundation (NSF)-university	0.5	0.5	0.5	0.5	0.5	2.5
Total estimated funding	21.3	28.1	34.4	34.4	28.0	146.2

[a]Includes NASA and DOD government laboratory research personnel costs.

5.2 RESEARCH FACILITIES AND EQUIPMENT

Extensive research facilities and sophisticated equipment will be required to implement this ceramic technology program properly. Many of the facilities exist in industry, government laboratories, and universities but are not used to full capacity because of a lack of research funding. The major ceramic and engine manufacturers, industrial research centers, and nonprofit research organizations have invested substantially in new research facilities and equipment over the past five years, and a number of relevant new university research centers have recently been established. In addition to the existing facilities at government laboratories, some new facilities are under construction (e.g., the National Synchrotron Light Source at Brookhaven National Laboratory) or are planned for construction (e.g., the High-Temperature Materials Laboratory at ORNL).

Although much of the equipment required for this research is available at various laboratories, some new equipment will be needed. Specific needs include process control equipment in industry and equipment for characterizing materials properties at industrial, government, and university laboratories. Industry is expected to provide funding for most of the process control equipment required; the government-funded equipment needs for this program are estimated to be $8 million.

6. PROCUREMENT PLAN

6.1 PROCUREMENT PROCEDURES

To achieve the objectives of this program, the cooperative involvement of U.S. industrial, government laboratory, and university research communities is required. The major roles of ORNL in managing this program are to encourage the participation of qualified subcontractors, to coordinate the various R&D activities closely, and to disseminate the results of these activities to the appropriate program participants and government agencies. Because ORNL will be subcontracting most of the program funding, informing potential subcontractors of the current procurement policies is important.

In general, the R&D will be accomplished by Martin Marietta Energy Systems, Inc., subcontracts with industrial research centers and universities and by DOE laboratories and other government research laboratories according to their staff and facility capabilities and their responsiveness to program needs. Regardless of the procurement instrument, all statements of technical scope shall be approved by OVERD.

Industrial and university participants may be selected on the basis of research proposals submitted in response to either a request for proposal (RFP) or a program research and development announcement.

In most cases research of a specific nature is required, particularly from an industrial source; therefore, research proposals will be solicited by a Martin Marietta Energy System RFP. Proposals submitted in response to Martin Marietta Energy System RFPs will be evaluated on technical merit by a technical evaluation team chosen by the project manager. This team will include participation by technical experts acting as technical advisors and may include representatives from OVERD, ORO, or other government agencies. Any information designated as proprietary shall be limited to evaluators signing a proprietary agreement. A proposal based on the results of the technical evaluation will be selected for a subcontract award by a Martin Marietta Energy System subcontract selection team. The subcontract selection team will be composed of technically and contractually qualified Martin Marietta Energy System personnel, to be chosen by ORNL and the Martin Marietta Enegy System Purchasing Division in conformance with DOE-ORO-approved procurement procedures.

For generally defined areas of research interest, program research and development announcement drafts will be developed by ORNL and submitted to ORO for issuance as DOE-ORO program research and development announcements in accordance with DOE procurement regulations. These announcements may provide for the award of Martin Marietta Energy System subcontracts for the proposals selected by DOE-ORO. All proposals will first be reviewed and evaluated by an ORNL technical evaluation team. The ORNL technical manager will advise the DOE-ORO selection panel and provide the results of the ORNL technical evaluation team for the information of the selection panel.

Although most procurements will result from a competitive selection process, sole-source subcontracts will be executed when one source has exclusive capability to perform the work within the time required and at a reasonable price. Any unsolicited proposal should be submitted to DOE for processing and appropriate action, in accordance with DOE procurement regulations.

For R&D that might best be performed by other DOE laboratories, procurement will be accomplished by an ORNL Martin Marietta Enegy Systems memorandum purchase order or direct financial plan change by OVERD. The ORO will coordinate any necessary approvals with those field offices having purview over the concerned laboratory. In those instances in which R&D assistance is desired from a non-DOE government laboratory, ORO will negotiate an interagency agreement with the other agency for program assistance.

6.2 ASSIGNMENT OF PATENT RIGHTS

As a result of the passage of Public Law 96-517, previous rules on patent rights of individuals, educational institutions, business firms, and the government have been modified. Rule changes relate to ownership, disclosure, and commercial development of patented information and equipment and components. Generally, small businesses or nonprofit organizations within the meaning of Public Law 96-517 (Sect. 201, Chap. 38 of Title of the U.S. Code) can secure greater patent rights than set forth in the DOE procurement regulations (Chap. 9-9). For other subcontractors not directly affected by the recent statute, experience has been that a patent waiver under DOE procurement regulations will be granted only if there is a waiver of subcontract fee plus cost sharing of 20% or more.

Any firm considering participation in the program must become familiar with the current DOE patent policies. Further changes are expected to induce additional participation in this and other programs in the future. Prospective contractor's patent rights and retention of technical data will be negotiated case by case.

7. REFERENCES

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APPENDIXES

Appendix A

SPECIFIC CERAMIC TECHNOLOGY NEEDED FOR ADVANCED GAS TURBINE AND ADIABATIC DIESEL ENGINES

As noted by the industry-needs assessment, specific ceramic technology needs and technical objectives depend on the expected service environment. Because this plan focuses on the advanced heat engines requiring ceramics, the technical objectives for advanced gas turbine and adiabatic diesel components are emphasized. However, many of these objectives are generic and applicable to other advanced engine components and industrial products.

The development of reliable ceramics capable of being fabricated by low-cost processing techniques is recognized as the key technology needed for high-efficiency cost-effective advanced gas turbine and diesel engines for automotive applications. The use of ceramic components in these engines is in a relatively early stage of development compared with that of the high-cost superalloys used in high-performance aircraft engines. The technological developments required for ceramics are also more demanding; ceramics are brittle and difficult to fabricate reproducibly, particularly in the complex shapes required for high-efficiency gas turbines. Because of the sensitivity of ceramics to small inherent flaws, wide variations in fracture-strength behavior are observed, and statistical design approaches are required to obtain low fracture probabilities. To achieve high reliability, a number of generic research issues must be resolved, including the following:

- basic understanding of the interrelationships among processing, microstructure, microchemistry, and strength;
- material processing improvements to achieve greater material uniformity and strength;
- development of low-cost processing techniques;
- improvement of processing equipment, including use of improved in-process instrumentation and microprocessor controls;
- development of reproducible and cost-effective sources of powders and fibers for monolithic and composite ceramics;
- development of new ceramic microstructures yielding high toughness and increased strain tolerance;
- material and component quality control techniques and specification development and verification;
- material and design studies to understand the mechanisms causing high-temperature contact stress and to determine solutions;

- development of low-friction compliant ceramic coatings or other interface designs to minimize contact stress at critical interfaces; and
- development of a data base for strength, creep, toughness, fatigue, and environmental effects from ambient to the maximum operating temperature range of 900 to 1510°C (1650–2750°F) and evolution of a life prediction and design methodology.

A.1 MATERIALS TECHNOLOGY NEEDED FOR ADVANCED GAS TURBINES

Following are descriptions of some specific technology and property objectives for different categories of advanced gas turbines.

A.1.1 Gas Turbine Rotor

The rotor typically is exposed to the highest mechanical stress of all of the components in a turbine engine. Depending on the design and application, the peak tensile stress during maximum power operation ranges from 210 to 350 MPa (30–50 ksi) in the hub region of the rotor. This high level of stress is present in a large volume of the ceramic material and can be sustained only by a high-strength ceramic material containing no flaws larger than a few micrometers. Material average strength [four-point bending, 38-mm (1.5-in.) outer span] of about 620 MPa (90 ksi) with a Weibull modulus in excess of 12 appears to be necessary for high-reliability ceramic rotors. Furthermore, the material must be able to maintain a major portion of this strength up to about 1100°C (2000°F) and be unaffected by cyclic thermal shock and long-term oxidation-corrosion exposure of engine operation.

In addition to the generic technology needs described above, the gas turbine rotor has specific requirements, including development of a reliable attachment technology; iteration between rotor fabrication, design, and testing to demonstrate reliability; and development of improved resistance of ceramics to impact damage.

A.1.2 Gas Turbine Stator

The gas turbine stator has different design and material requirements from those of the rotor. The stator is exposed to higher temperatures [1200–1510°C (2200–2750°F)] than is the rotor and must be fabricated from a material that does not degrade at these temperatures from oxidation, corrosion, creep, slow crack growth, or thermal fatigue.

The major stresses in the stator are thermal and can generally be held under 210 MPa (30 ksi) by proper design. Existing monolithic ceramics (SiC and Si_3N_4) with flexure strengths ranging from 275 to 415 MPa (40–60 ksi) have demonstrated that they can survive the thermal stresses for short to moderate times (200–500 h). However, the results have not been reproducible from batch to batch because of variability in the materials. Furthermore, some stators have fractured because of localized contact stress at ceramic-ceramic or ceramic-metal interfaces in the engine, especially when interface adhesion has developed at high temperatures.

In addition to the generic technology needs described above, iteration between stator fabrication, design, and testing is needed to demonstrate reliability.

The previously used approach to material development for the stator has been to achieve improved strength of monolithic ceramics. This approach is valid and has yielded some successful component demonstrations but is not the only approach and may not be the optimum approach. An alternative with much potential is the use of a composite microstructure to achieve specific properties. For instance, a composite material with a low bulk elastic modulus would be more strain tolerant than would a monolithic ceramic and would have greater resistance to thermal shock, contact stress, and impact.

A.1.3 Gas Turbine Static Structure

The gas turbine static structure includes transition liners, housings, plenums, and other ceramic flow-control or support structures. Temperatures can range from hot spots above 1370°C (2500°F) at the turbine inlet to below 980°C (1800°F) at the turbine exit. The major stresses are thermal.

The static structure components are typically large and contain a greater volume and surface area of ceramic material than does either the rotor or stator. The current sizes and shapes identified for advanced automotive prototype engines continue to challenge ceramic manufacturers. It appears that considerable process development (and possibly equipment development) will be required to achieve uniformity of the ceramic material in these large components.

As with the stator, prior development of static structure components has utilized monolithic ceramic materials. The option of ceramic composites needs to be pursued with the objective of demonstrating materials that are suitable for lower stress designs and have greater toughness and strain tolerance. Another option for reducing thermal stresses is to develop high-strength very low-expansion ceramics. Current commercial materials in this category have marginal temperature capability and strength, but new compositions provide much potential for improvement.

Most of the technology needed for gas turbine stators also applies to these other static structure components. The major differences involve the larger size and volume requirements for such components (especially the associated problems of fabrication equipment limitations and achievement of microstructural uniformity in such large parts) plus the necessity for increased effort on high-toughness composite microstructures.

A.1.4 Gas Turbine Combustors

The combustor is listed separately from other static structure components because of the unique design and materials requirements associated with low-emission specifications. Advanced combustors are likely to be of multipiece design, possibly containing more than one type of ceramic material and including critical metal and ceramic interfaces. Controlling temperature to minimize thermal stresses and to avoid coking of fuel will be a major development requirement. This will be especially true for engines with heat recovery in which the inlet air to the combustor will be typically above 925°C (1700°F).

The technology requirements identified for the ceramic stator and static structure also apply to the combustor. In addition, special machining or finishing techniques may be necessary to control air flow and fuel flow and to avoid clogging or coking. Careful attention to contact stresses will also be important for interfaces between separate pieces of the combustor and between similar or dissimilar materials.

A.1.5 Regenerator

Materials and designs have been demonstrated for a 980°C (1800°F) regenerator. The major directions for improvement of the current system are to reduce leakage (especially around the seals) and seal drag. This will primarily involve coating development and improvement of friction and wear characteristics.

Advanced regenerator systems require higher temperature capability. Higher temperature [980–1200°C (1800–2200°F)] regenerator core materials and seal materials must be developed and demonstrated. Key technology developments required include (1) development of a thermally and chemically stable regenerator core material capable of operating at a 1200°C (2200°F) material temperature and (2) development of an advanced high-temperature low-friction seal material that has the erosion and wear resistance necessary to function at least 3500 h in the regenerator system.

A.2 MATERIALS TECHNOLOGY NEEDED FOR ADVANCED DIESEL ENGINES

Heat losses over the operating cycle of current diesel engines represent about 30% (not including exhaust losses) of the chemical energy available in the fuel. These heat losses can be reduced in a number of ways; however, the most significant reductions can be achieved by using insulating ceramic coatings and/or liners in the combustion chambers of the engine. Insulation of the combustion chamber also increases the heat energy of the exhaust, which can be converted to useful power by turbocompounding or by other waste heat recovery techniques. Considerable progress has been made in demonstrating the feasibility and advantages of using ceramics for a turbocompounded adiabatic engine in the Cummins/TACOM military engine development program. A 16% reduction in fuel consumption was achieved with ZrO_2 coatings for critical combustion chamber components in an uncooled turbocompounded 185-kW (250-hp) engine. A 25% reduction has been demonstrated with thicker monolithic ZrO_2 piston liners and caps, head plate, valve seats and guides, and exhaust port insulation. If a minimum friction design is developed by use of ceramic pistons and cylinders, gas bearings in place of piston rings, ceramic roller bearings, and insulated valve trains and exhaust parts, a 37% reduction in fuel consumption is projected. For a light-duty [60-kW (80-hp)] minimum-friction engine in a 1360-kg (3000-lb) vehicle, the Environmental Protection Agency (EPA) combined cycle gas mileage is projected at about 30 km/L (70 mpg). These technology areas are generic to large adiabatic diesel engines and other advanced diesel engine concepts, such as a two-stroke opposed-piston engine with unlubricated ceramic cylinder liners and pistons for light-duty applications.

Following are descriptions of some specific technology and property requirements for critical ceramic components for the adiabatic and minimum-friction advanced diesel engine components.

A.2.1 Piston

The piston is subject to the highest mechanical and thermal stresses in the adiabatic diesel engine. Steady-state and cyclic stresses above 700 MPa (100 ksi) and surface temperatures as high as 1000°C (1832°F) are calculated for some designs. In addition, low thermal conductivity and heat capacity are required for maximum combustion efficiency. Design concepts to meet the requirements include ceramic-coated metal pistons, monolithic ceramic piston caps joined to metal pistons, or entire ceramic pistons attached to metal or ceramic connecting rods.

The thickness and therefore the insulating capability of current ceramic coatings is limited by the uniformity, strength, and interfacial bonding properties of coatings applied by conventional techniques. Although thin coatings have operated successfully for short times in diesel engines, improved properties and reliability must be developed for thick insulating coatings to achieve the full potential of adiabatic diesel engines.

Monolithic ceramic piston caps joined to metal pistons provide greater insulation and opportunities for using higher strength materials than do coatings. However, higher strength high-temperature insulating ceramics and ceramic-metal joining technology must be developed. Currently, partially stabilized ZrO_2 (PSZ) is being tested for this component. However, the limited high-temperature strength, thermal stability, and unknown behavior under cyclic stress and combustion environment conditions may prevent the use of this material for long-term applications. Various techniques for joining the piston cap to the metal piston are under development, including shrink fitting, mechanical joining, brazing, and combinations of these techniques. The reliability of these joints and possible development of new techniques must be established for long-term application.

For a minimum-friction adiabatic diesel engine, ceramic materials having low expansion, low thermal conductivity, and high strength are needed. Low expansion is needed to maintain proper clearances between the piston and cylinder over the range of thermal conditions for the gas bearing to be effective. High-temperature solid lubricants may also be required for long-term reliability.

A.2.2 Cylinder Liner

In a hybrid ceramic-metal adiabatic engine with piston rings, the cylinder liner is subject to severe wear but to lower mechanical and thermal stresses than is the piston. Because the heat loss through the cylinder is lower, ceramic coatings on steel liners may be usable if sufficiently low friction and wear properties can be developed along with reliable fabrication and inspection techniques.

Monolithic ceramic liners are being tested with limited success. Partially stabilized ZrO_2 liners show severe wear damage by the piston rings; although Al_2O_3 liners show less wear, they are difficult to assemble in the engine by shrink fitting because of the mismatch in thermal expansion with the cast-iron block. Use of a partial cylinder liner above the piston wear area may be feasible if the loss in thermal efficiency is acceptable. However, the development of a cost-effective wear-resistant ceramic liner is desirable. This may be possible through the development of improved materials, assembly techniques, or solid lubricants.

For the minimum-friction engine, a monolithic ceramic cylinder could be used, thus eliminating the metal block entirely. Requirements for the cylinder material are similar to those for the piston.

Appendix B
DETAILED RESEARCH PLAN

B.1 INTRODUCTION

This detailed research plan provides a comprehensive description of the research tasks required to achieve the goals and objectives of this program. The research tasks are organized in a work breakdown structure developed jointly by ORNL and NASA-LeRC. This work breakdown structure provides the framework for setting priorities of research tasks and for coordinating facilities with complementary research funded by other government agencies and by industry. The research plan describes the technical needs and objectives, the materials, and the approach employed for achieving improved reliability in the ceramic materials.

B.2 OBJECTIVES

The objective of the Ceramic Technology for Advanced Heat Engines Program is to develop the industrial technology base required for reliable ceramics for application in advanced vehicular heat engines. The goal of the program is to improve ceramics through development of new processes and new materials having superior mechanical, corrosion, and wear properties. Major emphasis is on identifying and understanding the mechanisms and processes that determine the long-term reliability of the candidate heat engine ceramics in heat engine environments and on identifying means for substantially increasing the reliability of these materials. An additional goal is to develop the technology base for dynamic interfaces and joints between these ceramics and themselves, other ceramic materials, and selected alloys.

The complex interrelationships among powder synthesis, powder properties, the fabrication and densification processes required to produce the ceramic materials, and the important mechanical and physical properties vital to the utilization of the ceramics in a particular component in a particular heat engine constitute a major focus of this program. In addition, the R&D conducted in this program consists of a highly coordinated set of activities conducted by a variety of researchers located in U.S. industrial, government laboratory, and university research groups.

The heat engines in which these ceramics may be applied include the advanced gas turbine, uncooled diesel (adiabatic), and Stirling engines. The materials studied in this program include sintered silicon nitride; sintered silicon carbide; sialons; transformation-toughened zirconia; low-expansion silicates; dispersion-toughened alumina-zirconia and alumina-hafnia; composites based on silicon carbide, silicon nitride, alumina, and zirconia; and a variety of dense wear-resistant ceramic coatings for engine alloys.

The understanding and control of the flaw populations in laboratory specimens will be translated to satisfy engine component technology needs by using suitably selected simulated engine components. It is critical to demonstrate that property improvements achieved in experimental specimens in this program can be accomplished in configurations meaningful to the U.S. heat engine community.

B.3 APPROACH

The approach used in this program to accomplish the objectives is to organize the technical work within the framework of the work breakdown structure, based on three major program elements: materials and processing, design methodology, and data base and life prediction. Each of these major program elements is in turn organized into subelements. Figure B.1 illustrates the organization of the program elements. Diagrams depicting the individual work breakdown structure of each element are located appropriately throughout the following text. This section of the detailed research plan briefly describes the general content of the work breakdown structure.

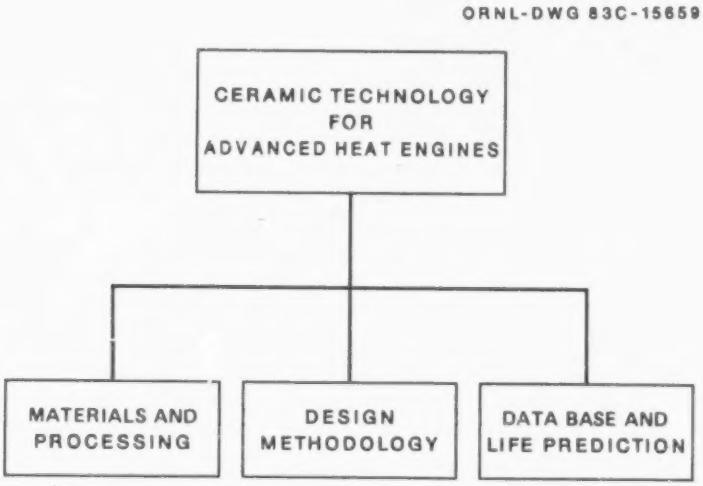

Fig. B.1. Program elements for the Ceramic Technology for Advanced Heat Engines Program.

B.3.1 Program Element 1—Materials and Processing

This program element is organized as shown in Fig. B.2 and includes four subelements: monolithic ceramics, ceramic composites, thermal and wear coatings, and joining. A brief description of the ceramic materials and systems to be studied in each subelement, the approach to be employed in conducting the technical work, and the purpose for conducting the work follow.

B.3.1.1 Subelement 1.1—monolithic ceramics

Three classes of monolithic ceramics (nonoxides, oxides, and silicates) are included. Organization of this subelement is shown in Fig. B.3. Nonoxide ceramics will include SiC, Si_3N_4, and sialon (silicon oxynitride). Oxide ceramics will include only ZrO_2, Al_2O_3, and possibly one other type. Silicate ceramics will include lithium aluminosilicate (LAS), aluminum silicate (AS), and magnesium aluminosilicate (MAS). The research methodology employed in conducting the technical work in

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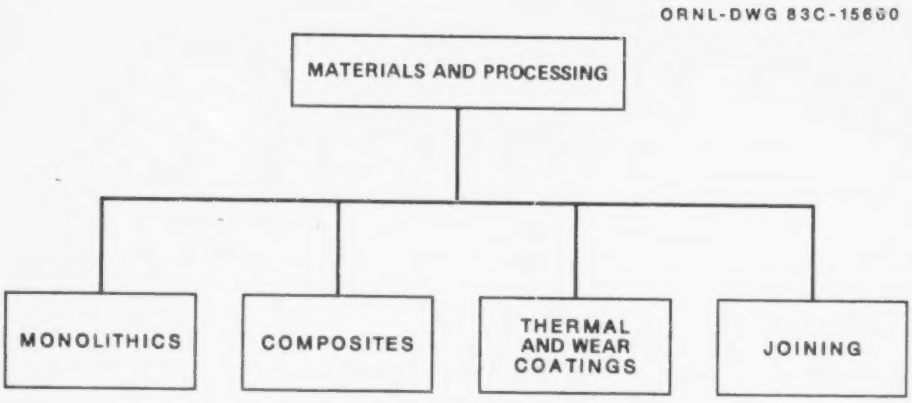

Fig. B.2. Subelements of program element 1, materials and processing.

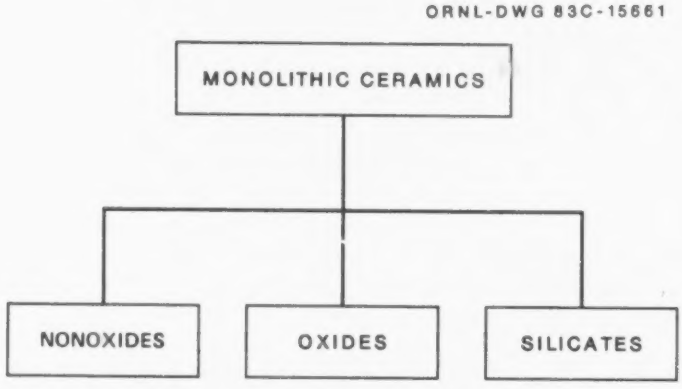

Fig. B.3. Classes of material for the monolithic ceramic subelement of program element 1.

this subelement on these materials includes the following major research tasks: (1) powder synthesis and characterization, (2) processing and characterization of green-state ceramics, (3) densification of green-state ceramics, (4) structural properties of dense ceramics, and (5) mechanical and physical properties of dense ceramics. The organization illustrated for Si_3N_4 ceramics is shown in Fig. B.4 as an example for all the monolithic ceramics. The strategy and content of each of these research tasks follow.

Powder synthesis and characterization. The strategy of this task is to achieve major improvements in the quantitative understanding of how to produce powders of the requisite compounds such as SiC, Si_3N_4, LAS, and ZrO_2 having highly controlled particle size, shape, surface area, impurity content, and phase content. It is also necessary to improve available techniques substantially and to identify and develop new techniques needed to describe and specify these powders quantitatively.

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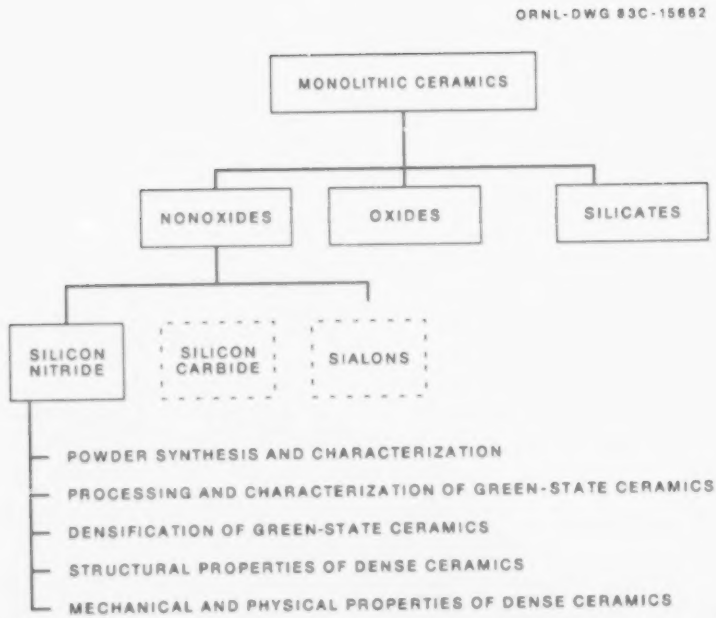

Fig. B.4. Organization example of work tasks for silicon nitride ceramics in monolithic subelement of program element 1.

The approach will include investigating advanced vapor phase, organometallic, solid-state reaction, and aqueous-base processes with the goal of synthesizing highly controlled submicron powders of the requisite materials. In addition, substantial efforts will be devoted to developing new and improved techniques for rapidly determining the required powder properties.

Processing and characterizing green-state ceramics. The strategy of this task is to produce major improvements in understanding ceramic powder and carrier systems so that the behavior of ceramic particles in the liquid or polymeric carriers and mechanical systems necessary for near-net-shape fabrication of heat engine components in the green state is advanced sufficiently to permit fabrication of highly reproducible uniform green bodies in the complex geometries required for these components. The approach includes studies of ceramic particle, polymer, and chemical carrier systems; studies of hydrodynamics and rheology of these mixtures; and the development and application of techniques for rapidly determining the spatial uniformity of the densities on a microscale and other properties of the resultant green-state ceramics. Carrier systems of interest include those relevant to green-state fabrication by injection molding, slip casting, and other processes of potential interest in near-net-shape forming ceramic heat engine components.

The ceramic materials studied in this task are the same as those investigated in the powder synthesis and characterization task, namely the nonoxides SiC, Si_3N_4, and sialons; the oxides Al_2O_3 and ZrO_2 (plus perhaps one other oxide); and the silicates LAS, AS, and MAS.

43

Green-state processing emphasizes efforts directed to processes capable of forming the ceramic to or nearly to the net shape required for prototypical engine components of that material. Examples include gas turbine rotors, stators, and combustor liners of SiC and Si_3N_4 and uncooled diesel cylinder liners, piston caps, and valve components of ZrO_2-base ceramics.

Densification of green-state ceramics. The strategy of this task is to achieve such a major improvement in understanding the densification process in the candidate monolithic ceramics that two goals can be achieved: (1) the green-state materials can be densified at high temperatures so that they have highly reproducible density and shrinkage factors and (2) the densification process results in highly uniform and reproducible mechanical properties in the ceramic materials.

The monolithic ceramic materials studied in this task are the same as those investigated in tasks 1 and 2, powder synthesis and characterization and processing and characterization of green-state ceramics. Densification studies in this task primarily involve the powders and green-state ceramics resulting from these previously described tasks. The approach to be employed in this task has two parts: parametric studies and basic studies.

Parametric studies. The goal of these studies is to determine the parametric relationships among final density, densification shrinkage, and microscopic uniformity of final microstructure of the monolithic ceramics as functions of several variables, including initial composition, powder properties, green-state properties, time-temperature history to achieve densification, and the atmospheric composition and pressure employed during the densification process.

Basic studies. The goal of these studies is to determine certain fundamental properties of the candidate ceramic systems for obtaining an improved understanding of the complex and presently poorly understood set of processes that occur when an assembly of ceramic powder particles interacts at high temperatures and densifies. Several fundamental needs exist in this area, including phase equilibria, chemical diffusivities of major elements, sintering kinetics, behavior of sintering aids, and analytical sintering models, which include solid-state diffusion, liquid-phase transport, and vapor-phase transport.

Structural properties of dense ceramics. The term *structural properties* as used in this task includes both the microstructure and crystal structure of all major and minor phases in the monolithic ceramics investigated in this subelement. The strategy for the work is to organize and conduct investigations of the dense monolithic ceramic materials that result from the densification task. The goal is to obtain nanometer-scale quantitative microstructural and phase descriptions of the as-densified (virgin) monolithic ceramics resulting from the preceding powder, green-state processing, and densification of each of the candidate ceramics. The approach used includes application of optical microscopy, scanning electron microscopy, analytical electron microscopy, laser Raman spectroscopy, macro x-ray diffraction, micro x-ray diffraction, Auger spectroscopy, and other techniques to provide required microstructural information.

Mechanical and physical properties of dense ceramics. The strategy for this task is to qualify a set of mechanical and physical property measurement techniques for use on monolithic ceramics and to employ these techniques to generate property data for the candidate monolithic ceramics resulting from the powder synthesis, green-state fabrication, and densification tasks. Mechanical and physical properties of principal interest in this task include those of the monolithic ceramics in their as-densified (virgin) state before the materials are subjected to long-term oxidation, corrosion,

or application of stress. Mechanical properties of principal interest in this task include fast-fracture strength, fracture resistance, and elastic properties as functions of temperature. Fracture strength is measured under flexure, tensile, and biaxial stresses and is analyzed in terms of a statistical representation for brittle solids. The environments for these measurements include vacuum and air.

Particular attention is devoted to the fracture strength and fracture resistance measurement techniques with the objective of minimizing biases in the calculated property values from the measurement process itself so that highly reproducible and accurate fracture properties can be measured routinely. Methods for measuring elastic properties, including Young's modulus and Poisson's ratio, are standardized and implemented. Physical properties of major concern include thermal expansion, thermal conductivity, and thermal diffusivity measured to about 1300°C.

B.3.1.2 Subelement 1.2—ceramic composites

The work in this subelement comprises four classes of ceramic composite materials, including the matrix ceramics Si_3N_4, SiC, oxide, and silicate, as shown in Fig. B.5. The strategy of this subelement is to determine the mechanical properties of a variety of composites as functions of composition, green-state processing, and densification and to determine if either dispersoid particles or dispersed discontinuous ceramic fibers can significantly improve the fracture strength and fracture resistance of the four types of matrix phases shown in Fig. B.5. The research methodology to be employed for all four classes of composites is essentially identical to that employed in the monolithic ceramic subelement except for the addition of a task on fiber synthesis and characterization. The task structure by which this work is organized includes (1) powder synthesis and characterization, (2) fiber synthesis and characterization, (3) processing and characterization of green-state ceramics, (4) densification of green-state ceramics, (5) structural properties of ceramic composites, and (6) mechanical and physical properties of ceramic composites. The research tasks for the SiC matrix + fiber composites are shown in Fig. B.5 as an example for all the composite materials in this subelement. The composite systems investigated include (1) Si_3N_4 matrix + Si_3N_4 fibers, (2) Si_3N_4 matrix + second-phase particle dispersoid, (3) Si_3N_4 matrix + SiC fibers, (4) SiC matrix + SiC fibers, (5) SiC matrix + second-phase particle dispersoid, (6) SiC matrix + Si_3N_4 fibers, (7) ZrO_2 + second-phase particle dispersoid, and (8) Al_2O_3 + second-phase particle dispersoid or fibers.

The technical objectives of tasks 1, 3, 4, 5, and 6 in this subelement are essentially identical with those cited for tasks 1, 2, 3, 4, and 5 in subelement 1.1, monolithic ceramics, and therefore will not be discussed in detail here, except for particular exceptions.

Powder synthesis and characterization. All powder synthesis and characterization needs pertaining to Si_3N_4 and SiC powders in this subelement will be met with results from the powder synthesis task in subelement 1.1, monolithic ceramics.

It is anticipated that additional work on ZrO_2, Al_2O_3, and dispersoid powders will be necessary in this task in addition to that executed in subelement 1.1, task 1, because of the much less highly developed level of these ceramics compared with Si_3N_4 and SiC materials. In addition, work may be required on processes to produce submicron dispersoid metals and nonmetals if it becomes clear in the early exploratory work that useful dispersoid-phase distributions can substantially improve mechanical properties.

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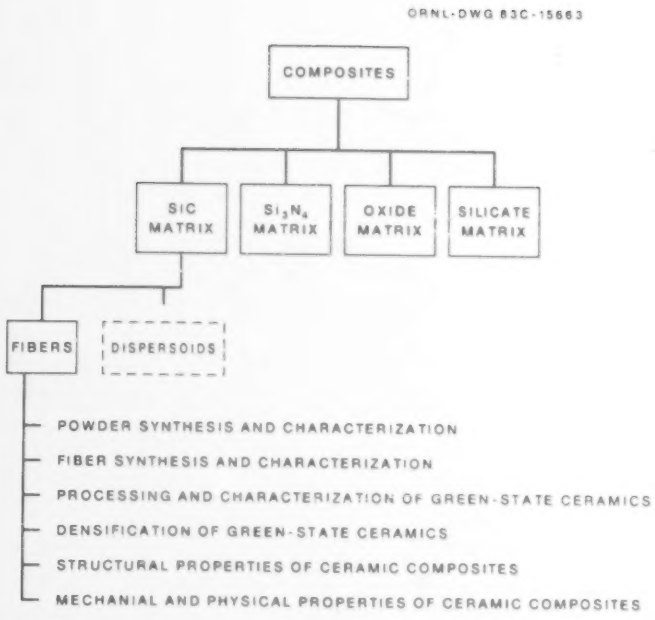

Fig. B.5. Organization example of work tasks for fiber-SiC composites of SiC matrix class in composite subelement of program element 1.

Fiber synthesis and characterization. The strategies of this task are to identify processes for synthesizing both Si_3N_4 and SiC fibers having a range of diameters and aspect ratios and to demonstrate that these processes can produce highly controlled fibers in quantities that make the processes attractive for eventual commercial application to ceramic composites. Fibers from this task will be used in the green-state processing and densification tasks in this subelement to produce experimental quantities of fiber-modified ceramic composites.

The approach includes investigation of vapor-phase, precursor, and other selected routes, with the objective of producing very high-strength fibers having highly controlled composition, structure, and geometry.

Processing and characterizing green-state ceramics. The major distinction between work conducted in this task and in the comparable task in subelement 1.1 involves identifying a means of mixing powders and fibers, blending or coprocessing a primary powder with a dispersoid powder, and determining a means of producing a desired dispersoid second phase from a precursor previously mixed with the primary ceramic powder of interest.

In the case of fibers, the goal is to identify ways to produce a green-state composite having a homogeneous isotropic fiber distribution without significantly damaging fibers mechanically. For dispersoid-phase composites, the goal is to achieve a highly homogeneous microscopic dispersion of the dispersoid phase in the primary ceramic matrix. These green-state materials are used in composite densification studies (described in task 4 of this subelement).

Densification of green-state ceramics. The major distinction between work conducted in this task and in the comparable task in subelement 1.1 involves investigations of densification processes to minimize relative particle-fiber movement within the microstructure at the high temperatures required for sintering the matrix phase in the fiber-containing composite systems and to minimize detrimental reactions between the fibers and the matrix phase. An additional difference between goals in this task and in the densification task in subelement 1.1 involves work in this task to identify densification procedures that will minimize detrimental reactions between the dispersoid phase and the matrix phase of composites that contain dispersoid particles. Agglomeration of the dispersoid phase during the high-temperature processing treatments required to achieve high-density ceramic composites must also be minimized.

Structural properties of ceramic composites. Structural properties of major interest in this task, in addition to those cited for task 4 of subelement 1.1, include details of the structure achieved during bonding at the interface between the surfaces of either the fiber or dispersoid-particle phase and the matrix phases. Interaction of the residual porosity in the matrix phase with both fibers and dispersoid particles at high composite densities and the effects of thermal expansion differences between major phases in the composites on microcracking and other processes that could be detrimental to their mechanical properties are of major interest. The subject materials for this task are those resulting from tasks 1, 2, 3, and 4 of this subelement.

Mechanical and physical properties of ceramic composites. The strategy of this task is to employ the qualified set of mechanical and physical property measurement techniques cited in task 5 of subelement 1.1 to generate required mechanical and physical property data for the ceramic composite materials resulting from tasks 1, 2, 3, and 4 of this subelement.

Mechanical properties of principal interest in this task include fast-fracture strength, fracture resistance, and elastic properties as functions of the processing variables and temperature in both inert atmospheres and air. The fast-fracture data are analyzed with a statistical representation of brittle solids fracture.

The major purpose of this task is to determine if ceramic composites resulting from the preceding tasks in this subelement exhibit mechanical properties sufficient to warrant detailed environmental and time-dependent property studies in element 3 and to provide mechanical property data for iterative feedback to the synthesis, processing, and densification task efforts in this subelement. Physical properties of major interest include thermal expansion, thermal conductivity, and thermal diffusivity as functions of temperature to about 1300°C.

B.3.1.3 Subelement 1.3—thermal and wear coatings

There is substantial need for high-reliability ceramic coatings for use on engine alloys to serve as

1. barriers to heat flow and transport of oxidative and corrosive species from hot gaseous engine atmospheres to underlying metal structures,
2. low-friction and wear surfaces between moving components in high-temperature engine environments, and
3. gas flow barriers in engine structures that are simultaneously in rubbing contact with other engine components.

The configuration that appears presently to be most promising for use of such coatings in engines is a relatively thin ceramic coating applied to a metal component. Substantial success in application of ceramic coatings to conventional metal engine components has been demonstrated for both conventional gas turbine and diesel engines.

The work in this subelement includes two major classes of ceramic coatings: oxide-base coatings and non-oxide-base coatings, as shown in Fig. B.6. Work in each of these coating classes is organized by the major phase(s) present in the coating.

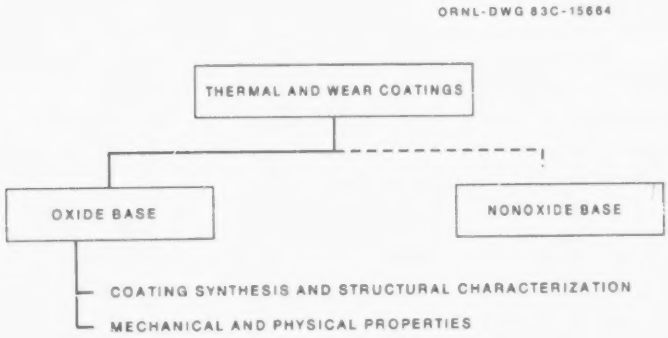

Fig. B.6. Organization example of work tasks for oxide-base ceramic coatings in thermal and wear coating subelement of program element 1.

Oxide-base ceramic coatings. Work is conducted on three major systems, two of which are specifically identified in this plan, and a third that may, in fact, include several systems based on later suggestions from the technical community. Major systems will include ZrO_2- and HfO_2-base coatings plus the third, which may include mixed-oxide systems.

Non-oxide-base ceramic coatings. Work is conducted on three major nonoxide systems, including carbide, nitride, and boride coatings. Specific compounds or mixed phases to be studied in this work will be identified later.

The technical activities for each coating system are organized into the two research tasks shown for oxide-base coatings in Fig. B.6: coating synthesis and structural characterization and mechanical and physical properties of ceramic coatings. The content, approach, and purpose of each of the two research tasks employed for both classes of coatings are essentially identical and are briefly described here.

Coating synthesis and structural characterization. The description for essentially all ceramic coating technology is that it is generally a well-evolved empirical technology, with oxide-base coatings being generally more mature than non-oxide-base coatings. Various ceramic coating synthesis techniques have been demonstrated and used commercially on a number of alloys, including plasma spraying, flame spraying, chemical vapor deposition, and chemical deposition.

The strategy to be employed in this task is structured both to address the substantial lack of fundamental understanding of coating technology and to build on the already substantial empirical technology base for ceramic coating synthesis. The coating synthesis work is organized into two parts: basic studies and applied studies.

Basic studies. Work in this part focuses on a very limited number of coating material systems and identified processes for producing the desired coatings on alloys of interest. The candidate coating materials, coating process(es), and alloy(s) will be selected later. Topics including coating residual stress, bonding mechanisms to the substrate alloy, and phase composition and microstructure are of major interest.

Applied studies. Work in this part of this subelement is more empirical and builds on the existing substantial technology base for coatings of at least some of the candidate materials. The approach will include development and demonstration of equipment and processes for synthesis of the coatings on engine alloys with the objective of controllably varying the coating microstructure, density, and properties. Key properties of the coatings from these studies are determined by the techniques identified and developed in the basic studies part of the work in this subelement. Long-term behavior of the more attractive coatings is evaluated in program element 3, data base and life prediction.

Mechanical and physical properties of ceramic coatings. The major objectives of this task include developing techniques for accurately determining certain mechanical and physical properties of relatively thin ceramic coatings deposited on a selection of alloys that have requisite properties for use in components of advanced heat engines. The measured coating property values obtained by these techniques are critical to determining and judging the progress in the coating synthesis work in this subelement.

Particular attention is given to identifying techniques for measuring meaningful mechanical and physical properties of thin ceramic coating specimens, both alone and bonded to their metal substrates, with the objective of measuring such properties with high accuracy. Properties of interest include but are not limited to fracture strength, fracture toughness, thermal conductivity, thermal diffusivity, and thermal expansion.

B.3.1.4 Subelement 1.4—joining

Joining of ceramic materials to other ceramic materials and to engine alloys to produce joints having requisite strength and stability is crucial to advanced heat engine technology. Joining processes involving ceramic materials have primarily evolved from technology developed over the past four decades for electronic devices. Currently known processes that have been employed with varying degrees of success include the use of both intermediate metallic layers in the joint structure and joints consisting completely of ceramic phases. Much more limited work has been performed on nonmetal approaches for joining ceramic materials to each other than on those employing metallic phases. Work in this subelement is organized into two classes: ceramic-to-ceramic joints and ceramic-to-metal joints, as shown in Fig. B.7.

The technical objective in producing either of these two types of joints is to bond materials together permanently so that the joint structure has the necessary strength and stability to serve its function in a heat engine. Work in the ceramic-to-ceramic joint class is organized into two parts: similar materials and dissimilar materials; work in the ceramic-to-metal joint class is organized into two parts also: oxides to iron-base alloys and nonoxides to superalloys or high-temperature alloys. Possibly a third part will be identified later.

For studies of ceramic-to-ceramic joints of both similar and dissimilar materials, the work is further organized into the research tasks illustrated in Fig. B.7: (1) joint formation processes,

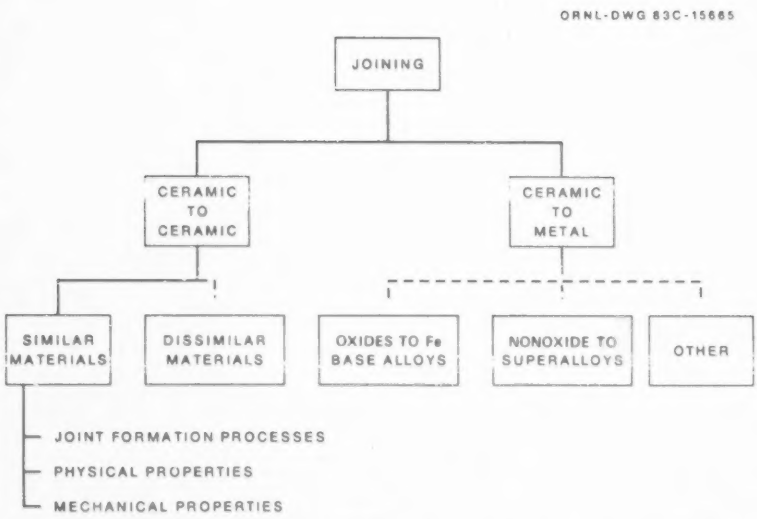

Fig. B.7. Organization example of work tasks for joining studies for similar materials in ceramic-to-ceramic joint class of joining subelement of program element 1.

(2) physical and structural properties of joints, and (3) mechanical properties of joints. Similarly, work in the ceramic-to-metal joints involving both oxide- and non-oxide-base ceramics is organized into these same three tasks.

Iron-base alloys for advanced diesel engines are employed, but superalloys or other high-temperature alloys for advanced turbine engines are emphasized. The approach first involves experimental joining studies to identify processes providing a range of joint microstructures and properties that can be developed over a range of processing temperatures.

In addition to experimental specimens, prototypical component configurations involving both oxide and nonoxide ceramics for both adiabatic and advanced gas turbine heat engine component joints are selected in consultation with heat engine manufacturers. The principal objective is to determine that positive experimental joining results obtained in the earlier part of this subelement can be translated to prototypical size components for existing or conceptual engines.

The purpose for conducting the work in this subelement is to develop a sound technical base of understanding for producing permanent joints with acceptable properties and structures of interest in advanced heat engines and to demonstrate that technical results obtained for relatively small experimental joints can be translated to selected prototypical size engine components.

B.3.2 Program Element 2—Design Methodology

This program element includes three major subelements: three-dimensional modeling, contact interfaces, and new concepts. The three subelements and the technical tasks for each are identified in Fig. B.8. A brief description of the technical content of the three subelements, the approach employed in conducting the technical work, and the purpose for conducting the work are also given.

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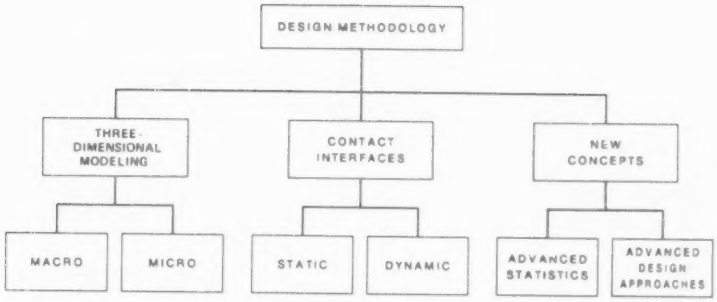

Fig. B.8. Work breakdown structure of program element 2, including three subelements.

B.3.2.1 Subelement 2.1—three-dimensional modeling

This subelement is organized into two tasks: macroscopic representations and microscopic representations.

Macroscopic representations. This task includes major emphasis on three-dimensional finite-element modeling of selected heat engine component geometries. The approach includes determining the precision and accuracy of current three-dimensional finite-element codes and boundary conditions that have been used in advanced heat engine programs to compute the stresses within brittle heat engine components. Improved methods for deriving the boundary conditions necessary for using these analytical codes will be developed as required.

Microscopic representations. This task involves testing the concept of using finite-element analytical methods for brittle solids on a dimensional scale equivalent to that of the microstructure in these materials. The purpose of this work is to determine if existing finite-element methods can be efficiently used for stress calculations in these materials when input variables include both the microstructural parameters of the materials and the imposed macroscopic boundary conditions.

The work in this task involves applying finite-element methods to model microstructure configurations, which include phases with and without plastic deformation, for analytically calculating stresses as a function of applied macroscopic stress and position within the microstructure.

B.3.2.2 Subelement 2.2—contact interfaces

This subelement is organized into two sections: static interfaces and dynamic interfaces, as shown in Fig. B.9. It includes the study of phenomena associated with static and moving interfaces between different ceramic materials and between ceramic materials and selected engine alloys. Any engine design includes numerous interfaces between ceramic components of different materials and between ceramic and alloy components. The strategy for this subelement is to organize and execute technical work whose results provide a much improved understanding of the behavior of both types of interfaces for selected pairs of materials under heat engine conditions; the work includes changes in static and dynamic friction and wear and abrasion of the materials as functions of temperature and time.

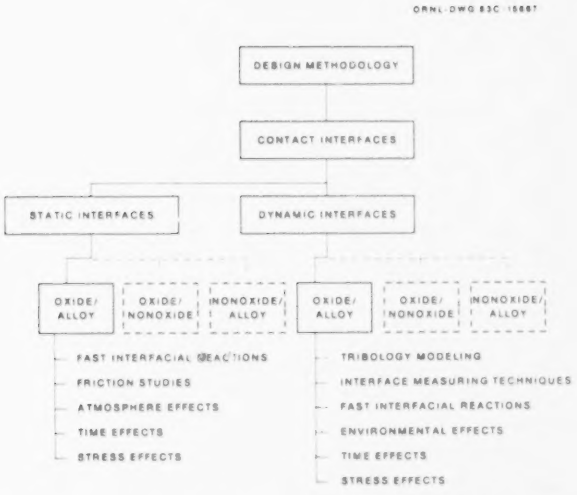

Fig. B.9. Organization of work tasks for contact interfaces subelement of program element 2.

The oxide-base ceramics studied include, but are not limited to, monolithic ZrO_2 and silicate materials and composites having ZrO_2 and Al_2O_3 matrices. Non-oxide-base ceramics studied include monolithic SiC and Si_3N_4 materials and composites having Si_3N_4 and SiC matrices. Ceramic coating systems studied include oxide-base coatings containing ZrO_2, HfO_2, or ZrO_2-HfO_2 solid solutions as the major phase and non-oxide-base coatings containing Si_3N_4, SiC, or other selected refractory carbides, nitrides, or borides as the major phase. The work on oxide-base ceramic and oxide- and non-oxide-base coatings that include an alloy as a member of an interface emphasizes iron-base alloys, while the work on non-oxide-base ceramics that include an alloy as a member of an interface emphasizes superalloys. As shown in the work breakdown structure (Fig. B.8) and as noted previously, work in this subelement is organized into static interfaces and dynamic interfaces. Each section is organized into the following material classes: (1) oxide ceramic–alloy interfaces, (2) oxide ceramic–nonoxide ceramic interfaces, and (3) nonoxide ceramic–alloy interfaces, as is shown in Fig. B.9.

Static interface section. Work on static interfaces for each material class is further organized into the following tasks: (1) fast interfacial reactions, (2) friction studies, (3) atmospheric effects, (4) time effects, and (5) stress effects.

Fast interfacial reaction task. This task is focused on identifying (1) phase reactions occurring in the interface between two materials in times up to about 50 h as a function of temperature, (2) comparison of the resulting interfacial-phase assemblage at the interface with phase equilibria predictions, and (3) analytical modeling to describe the kinetics of the observed phase reactions.

Friction studies task. This task concerns determining changes in the friction developed in the interface of the material pairs at high temperatures as a function of time up to about 50 h and

includes the development of experimental techniques for measuring interfacial friction developed at the interface between two materials for relatively simple experimental specimens. Correlations between results from this task and the task on fast interfacial reactions are used to derive and explain relationships between friction changes and interfacial phase reactions.

Atmospheric effects task. This task involves studies to determine the role of the gaseous atmosphere surrounding a static interface between various ceramic materials or ceramic materials and alloys in effecting phase reactions, interfacial sticking or bonding, and the resulting frictional resistance to interfacial displacement. The major atmospheric variable employed is the oxygen potential or oxygen partial pressure. Studies of material pairs in this task are conducted at a limited number of selected temperatures.

Time effects task. This task includes studies of how length of time at high temperature affects the interfacial friction and so forth of a variety of material pairs. The results obtained on static interfacial problem areas identified in the preceding tasks are used to select material pair, atmosphere, and applied static interfacial stress.

Stress effects task. This task includes studies of the role of cyclic stress on changes in friction and so forth at a static interface between materials under selected temperature, atmosphere, and time. In contrast to the fixed stress conditions used in previously described tasks in this section, work in this task is focused on understanding the role of cyclic compressive and shear stress and cyclic tangential strain in a material interface on the frictional behavior of that interface.

Dynamic interface section. Work on dynamic or moving interfaces is conducted for the same three material classes of monolithics and coatings noted previously (i.e., oxide ceramic–alloy interfaces, oxide ceramic–nonoxide ceramic interfaces, and nonoxide ceramic–alloy interfaces). The work in each of these material classes is organized into the following research tasks, as shown in Fig. B.9: (1) tribology modeling, (2) interface measurement techniques, (3) fast interfacial reactions, (4) environmental effects, (5) time effects, and (6) stress effects.

The objective of this program section is to develop a generic understanding of the friction and wear behavior of material interfaces at temperatures from about 500 to about 1200°C between ceramic and alloy materials in which the materials move with respect to each other in the plane of the interface.

Tribology modeling task. This task includes analytical and mechanistic modeling of the interface surface between two materials in which the stress and velocity are included as variables in addition to material properties. The goal of this subtask is to develop a model capable of accurately predicting the interfacial friction and wear as functions of the independent variables, including time, stress, and velocity, and the temperature dependence of the properties of the two materials and other species, such as lubricants, in the interface.

Interface measurement techniques task. This task includes developing experimental measurement techniques for quantitatively determining interfacial friction of laboratory-type material pairs so that the friction can be measured as a function of normal compressive stress, relative material velocity, temperature, amount and type of lubricant present, gaseous atmosphere surrounding the materials constituting the interface, and time.

Fast interfacial reactions task. This task includes work employing material pairs from the three material classes and focuses on obtaining an understanding of the reactions that occur at the interface of a material pair in air during relative motion over a range of velocities, applied stress, displacement, and temperatures relevant to advanced heat engine conditions by use of a small number of imposed compressive stresses.

Environmental effects task. This task includes studies to identify the role of gaseous, liquid, and solid species environments in addition to air in controlling the formation of new phases at the dynamic interface and to identify the role of these environments in determining the dynamic friction and wear of the materials of a given interface pair. Friction at the interface and surface wear of the materials as a function of temperature and the environment, including various oxygen potentials, liquid, and solid lubricants, are of major interest.

Time effects task. This task includes studies of the effect of time at high temperature on the friction and wear occurring at a moving interface between ceramic and alloy materials as a function of the materials, lubricants, and gaseous atmosphere. Techniques developed in the interface measurement task and others are used to determine the required properties. Material pairs, lubricants, and so forth selected for emphasis in this task are chosen on the basis of results obtained in other dynamic interface tasks and recommendations of the heat engine community.

Stress effects task. This task includes studies of the role of cyclic stress applied to dynamic interfaces between materials under selected temperature, atmosphere, lubricant, and time conditions. One objective is to identify the role of cyclic stress in the plane of the dynamic interface in determining the high-temperature friction and wear behavior of the selected material pairs.

B.3.2.3 Subelement 2.3—new concepts

This subelement is organized into two sections: advanced statistical representations of brittle solids and advanced brittle material design methodologies, as indicated in the work breakdown structure diagram (Fig. B.8).

Advanced statistical representations of brittle solids. As a result of the brittle fracture behavior of ceramic materials (i.e., the lack of plastic deformation processes at the crack tip and their resulting sensitivity to flaws of microscopic size plus the current relatively wide variability of flaw sizes in the microstructures of these materials), the fracture behavior of a given population of ceramic specimens typically exhibits a wide range of strength values about the average compared with metals. To utilize the fracture-strength distribution typical of ceramic materials in an analytical design methodology for engine components, the observed strength distributions must be analytically describable. Furthermore, a properly selected analytical description that relates the flaws, the applied stress, and the probability of fracture is a powerful tool for studying and understanding the behavior of these flaws, which in turn determine the mechanical reliability in this class of materials. The term *reliability* as used in the ceramic community and as used in this program is basically an acceptable failure or fracture probability.

The ability to design highly stressed engine components from ceramic materials therefore requires a detailed understanding of the statistical nature of fracture in brittle materials. The fracture strength of ceramic materials depends greatly on the range of flaw sizes present in the materials and on the stressed volume. Very little is known about changes in flaw populations in these materials at high temperatures in the presence of stress for long times.

A critical test to determine if a single flaw population, or Weibull representation, is valid for a given material is the demonstration that fracture data for a specimen population describe a straight line when $\ln \ln[1/(1-P_f)]$ is plotted against $\ln \sigma_f$, where P_f is the fracture probability and σ_f is the fracture stress. If multiple-flaw populations are present or if the Weibull representation is inappropriate, this type of graph clearly indicates that a straight-line description of the data is invalid.

Furthermore, if fracture data for a given ceramic material indicate that the presence of stress or exposure to high temperatures or both result in substantial changes in the value of either the Weibull modulus m or the characteristic strength σ_0 derived from the Weibull analysis, then the present methodology employed in brittle materials design does not contain a means for employing these changes.

This section of the program involves developing formalisms for including such changes in the analytical models so that fracture behavior results obtained for these materials in the environmental effects and time-dependent behavior subelements of program element 3, data base and life prediction, can be properly incorporated into failure probability determinations of components.

Advanced brittle material design methodologies. This section incorporates results from the task on advanced statistical representation of brittle solids section into the formalisms now used for heat engine component design. It includes calculations of fracture probabilities of simulated engine components by use of Weibull or other selected bases in which the flaw population varies with time.

B.3.3 Program Element 3—Data Base and Life Prediction

This program element is organized into the subelements indicated in the work breakdown structure diagram (Fig. B.10). These subelements include (1) structural qualification, (2) environmental effects, (3) time-dependent behavior, (4) fracture mechanics, and (5) nondestructive evaluation.

Work in this program element includes the development of techniques, generation of concepts, and acquisition of data necessary to advance the mechanical reliability of ceramic materials.

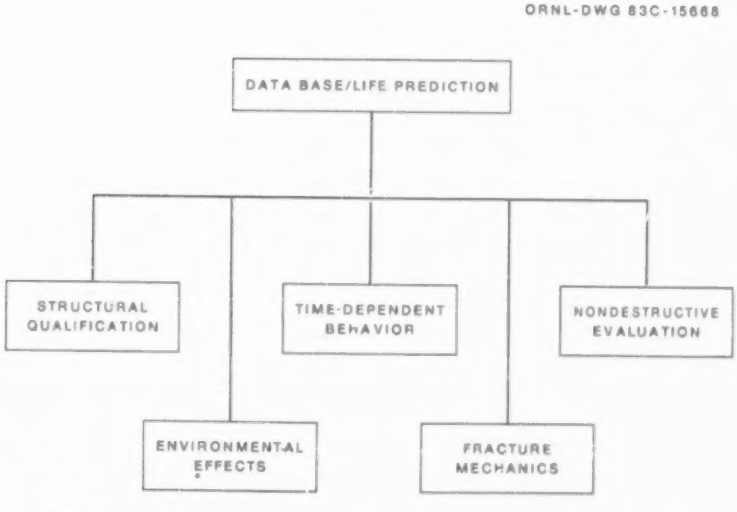

Fig. B.10. Five-subelement organization of program element 3, data base and life prediction.

B.3.3.1 Subelement 3.1—structural qualification

This subelement is organized into the four tasks shown in Fig. B.11: (1) proof testing concepts and verification, (2) correlations with NDE results, (3) correlations with microstructure, and (4) application to components.

Proof-testing concepts and verification. This task includes critical assessments of current proof-testing concepts for brittle materials, with particular emphasis on the applicability of proof-testing concepts for materials having unstable flaw populations.

The technical approach includes studies of populations of experimental specimens and prototypical components fabricated from at least three of the principal candidate ceramics considered appropriate for heat engines, with the objective of determining if current or new proof-testing concepts are meaningful for these materials. This task includes studies of the fracture behavior of survivors of proof-tested populations in which these survivors are subjected to stress at high temperatures for long time periods in simulated heat engine environments.

Correlations with NDE results. The strategy for work in this task is to closely couple the results of NDE measurements on specific populations of ceramic specimens with pre- and post-proof-tested populations for determining if any NDE techniques now available are capable of identifying members of a population of ceramic specimens that will fracture below a given proof-testing stress before they are fractured in the test. This objective is extremely important because success in this endeavor could avoid the requirement for proof testing entirely.

Results from this work indicate whether current NDE techniques are capable of reliably ranking a given population of ceramic specimens according to their subsequent location in the fracture-strength distribution both before and after application of a proof-testing stress.

Correlations with microstructure. This task involves the same population sets and subsets prepared for and used in the preceding task. This work includes fracture surface analysis and other

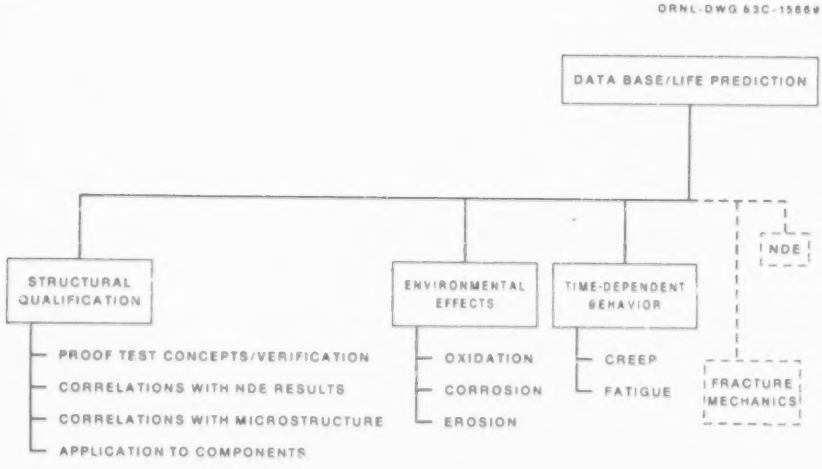

Fig. B.11. Work task organization for three subelements of program element 3.

microstructural analyses of selected specimens from the general and subset populations of a given ceramic material (both before and after proof testing). The purpose of the work is to identify the location and nature of the fracture origin in the specimens and to determine if the NDE results can indicate the location of the critical flaw from which fracture initiates in specific stressed regions in specific specimens.

Application to components. On the basis of successfully finding statistically significant correlations in the proof-test/NDE/fracture studies by use of relatively simple ceramic specimens, this task includes extension of the same methodology as that used in the preceding tasks in this subelement to a selected number of either prototypical or actual engine components of a few of the candidate ceramic materials. The work in this task focuses primarily on the questions (1) Can any of the known and available NDE techniques capable of detecting microscopically small flaws in ceramic materials with simple specimen shapes be applied usefully to components having more complex shapes? (2) Are the known proof-testing concepts applicable to real components when the ceramic components are subjected to high stresses at high temperatures for long time periods? The engine component test rigs developed under the current advanced gas turbine and diesel engine programs will be used for these evaluations.

B.3.3.2 Subelement 3.2—environmental effects

This subelement is concerned with the mechanisms for oxidation, corrosion, and erosion for selected candidate heat engine ceramics. Results from this subelement will be used with those in the time-dependent behavior subelement (described subsequently) to identify those materials that suffer the least mechancial property degradation during long times at high temperatures and to provide guidance for the materials and processing work in program element 1 to assist in developing ceramics having improved oxidation, corrosion, and strength degradation properties in selected heat engine environments. This subelement is organized into the tasks shown in Fig. B.11: oxidation, corrosion, and erosion.

A general objective of work in this subelement is to develop a quantitative understanding of the oxidation, corrosion, and erosion behavior of selected ceramic materials resulting from the work in program element 1 as functions of temperature, oxidative corrodant species, and the character and impingement conditions of the eroding species on the surface. The specimens for all materials included will be exposed in both stressed and unstressed conditions for obtaining understanding of the interaction between the applied stress in the materials and their oxidation, corrosion, and erosion behavior.

Oxidation. The ceramic materials of primary interest in this task are the nonoxide types, described in program element 1. The primary active species used in this task is oxygen, and the major independent variables, excluding the materials, are the partial pressure of oxygen and temperature. Gas velocity at the surface of the material specimens may also be varied for a limited number of experiments. Materials for studies are selected for obtaining oxidation data for a relatively large number of material variants (10 to 15) for relatively short exposure times and include both high-temperature microbalance techniques and exposures of substantial quantities of a given material in both generic and mechanical specimens. The material variants selected for this area are based partly on progress in program element 1.

Corrosion. The ceramic materials included in this program task include both non-oxide- and oxide-base monolithic and composite materials and coatings. Selection and restriction of the materials to a group of addressable size will be done later, but the total number will be restricted to fewer than five. The basic difference between this program task and the preceding one (i.e., oxidation) is that the exposure atmosphere employed in this task will include oxygen at a selected fixed partial pressure plus one (or a few) additional active species (e.g., Na, V, or S). The strategy for the work is to determine if the candidate ceramics have serious problems that involve long-term corrosion at high temperatures by species anticipated in the engine combustion gas environment. This environment can contain either elemental impurities from the fuel or from the engine's environment. The exposure atmosphere and temperature of interest for materials such as Si_3N_4 and ZrO_2 may be quite different if one is primarily considered for use in a gas turbine environment and the other is primarily considered for use in adiabatic diesels. The specific conditions to be used for each material will be selected later. Particularly important issues include changes in fracture strength distributions as a function of corrosion exposure time, temperature, and the presence and magnitude of applied stress.

Erosion. Ceramic materials included in this program task include non-oxide- and oxide-base monolithic and composite materials and coatings. Selection and restriction of the materials studied will be made later. This selection process will include identifying advanced heat engine areas in which erosion of hot component surfaces by particulate impingement is especially important, identifying the prime candidate ceramic materials for use in those components, and selecting a restricted set of materials from this list. A second selection process is used to identify no more than two erosive species along with temperatures, gas composition(s), gas velocity(ies), and range of expected particulate impingement angles.

B.3.3.3 Subelement 3.3—time-dependent behavior

This subelement includes studies of the time-dependent behavior of two mechanical properties for selection of the ceramic materials discussed in program element 1. Mechanical properties of principal interest include creep and fatigue, as shown in Fig. B.11. Materials to be studied in this subelement, to be selected later, include a selection of non-oxide- and oxide-base monolithic and composite ceramics and at least one material from the silicate group.

This subelement has the objective of obtaining understanding of both creep and fatigue in candidate ceramics selected from the materials discussed in program element 1. The acquisition of data for creep and for fatigue for the time periods of interest (up to 2000 h) is both very time consuming and expensive; therefore, the number of materials studied must be limited.

On the basis of the foregoing, the work in this subelement is organized into two tasks: creep and fatigue. Most of the work in both tasks is conducted on the same materials.

Creep. Creep measurements for ceramic materials can be conducted in several stress modes, including compression, tension, and flexure. Each of these stress modes will provide, for the same material at a given temperature and maximum stress value, a creep value that is different from that for the others. Conversion of creep values obtained from one stress mode cannot be readily converted into an equivalent creep value for another mode. Because of the relative simplicity of experimentally performing these measurements in flexure or compression on ceramic materials, the vast majority of creep studies of ceramic materials have been performed by use of these two stressing

modes. The tensile stress mode provides property data most relevant to the design of heat engine components. Tensile creep studies of ceramic materials have been rare because it is difficult to hold the specimens so that bending moments are not produced in the specimens from incorrect fixture alignment or friction in the specimen-holding fixtures, for example. These problems have caused most of the available fracture strength data for ceramics to be for the flexure stress mode.

Because of the importance of the tensile creep behavior of ceramic materials in engine component design, this task includes primarily tensile creep and flexural creep studies of the same materials. Studies of a very limited number of materials are also conducted in the compressive stress mode. The objectives of this work are (1) to obtain steady-state creep rates for the same material at the same temperature in the same atmosphere at the same peak stress in different stressing modes to determine if relatively simple correlations between creep rates for different modes can be established for these materials and (2) to generate a much improved basic understanding of the creep processes operative in the materials over a range of temperature, stress, and exposure atmosphere conditions.

The creep measurements for a given material are conducted in stress, temperature, and atmosphere regimes selected on the basis of the anticipated maximum stress and temperature appropriate for components of that material in advanced heat engines.

Fatigue. The term *fatigue*, as generally applied to ceramic materials, applies to changes in strength over time in the presence of stress in various environments. This concept is essentially identical to that involved in stress corrosion of metals, and the terms *fatigue* and *stress corrosion* are used more or less synonymously for ceramic materials. In metals, the concept of fatigue property measurements usually includes cyclic stresses or cyclic strains, and results are typically plotted for time to failure or fracture versus number of cycles of the imposed peak stress, peak strain, incremental stress, or incremental strain for a given set of temperature and other environmental conditions.

This subelement includes (1) selection of a restricted group of materials from those described in program element 1; (2) identification of the temperature regimes of major interest for those materials, based on their most likely use in components of advanced heat engines; (3) selection of the appropriate gaseous atmosphere to simulate the engine environment for those materials; (4) selection of the material specimen configuration(s) and the measurement methodology; (5) acquisition of the fatigue data; and (6) analysis of those data and the fractured specimens to obtain insight into the relationships among the fatigue behavior and the microstructure and microchemistry of the materials. These results are employed in program element 1 to improve the fatigue life and, thus, the reliability of the materials.

B.3.3.4 Subelement 3.4—fracture mechanics

This subelement includes the development and demonstration of improved measurement techniques for selected structural ceramic material properties that play a critical role in the analytical prediction of the fracture probability or reliability of the materials at high temperatures. The work is organized into three tasks concerned with these three properties (Fig. B.12): (1) critical stress intensity factor or fracture toughness K_{IC}, (2) subcritical crack growth velocity v_c, and (3) impact fracture toughness K_{ICI}. The scope and objectives for each of these tasks follow.

59

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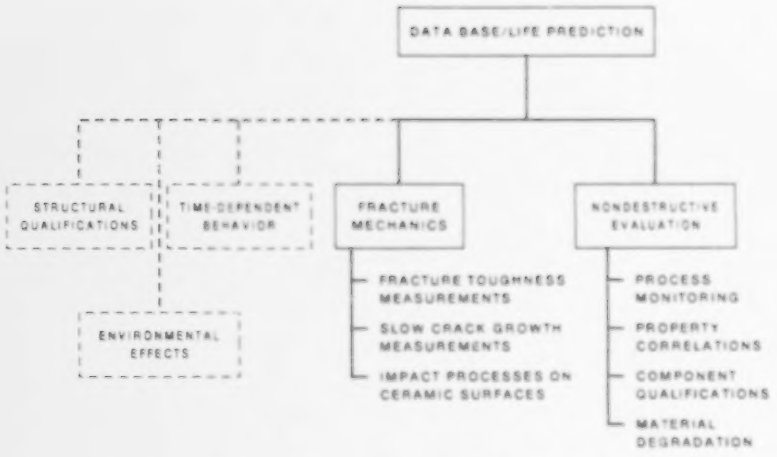

Fig. B.12. Work task organization for two subelements of program element 3.

Critical stress intensity factor (fracture toughness) K_{IC}. The critical stress intensity factor (fracture toughness or fracture resistance) of ceramic materials of interest for use in heat engines is a very important property in determining the reliability or lifetime of an engine component. Essentially all the ceramic materials that have been developed and evaluated for use in various heat engine components have low fracture toughness compared with alloys, with typical values being about 6 MPa $m^{1/2}$. Considerable effort has been expended in the United States and other countries in recent years to identify ways to increase the fracture resistance K_{IC} of ceramic materials.

This task is directed to conducting the required analyses to provide a method or methods for measuring K_{IC} or an equivalent property of candidate materials, including appropriate plasticity corrections, and demonstrating the validity of these analyses and measurement techniques by experimental measurements for one or more model materials selected from those cited in program element 1. These measurements are made as functions of temperature, time at temperature, and environment. Techniques developed for measuring fracture resistance will be used as the standard method of measuring this property for the appropriate materials in this program. In addition, experimental studies are conducted as required to provide supplementary data and properties that form the basis of the plastic deformation terms in the K_{IC} analyses if a linear elastic fracture mechanics approach is judged to be valid. These properties are derived as required from high-temperature creep and other measurements of the selected model materials.

Subcritical crack growth velocity. As discussed previously in this plan, the growth of microscopic cracks in ceramic materials is vitally important to determining the material's reliability under applied stress within a fracture mechanics context. The crack growth, which is considered to determine the time between the application of stress to the material and the time at which K_{IC} is attained for a given critical flaw, is thought to be dominated by "Region I" growth.

The focus of this task is primarily on demonstrating high-accuracy techniques for measuring the crack velocity in the materials of interest at temperatures and in atmospheres of major interest in advanced heat engines. The exponent n is a measure of the sensitivity of a given ceramic material to subcritical crack growth under a given set of conditions, in which high n values indicate low sensitivity. Materials with high n values are the goal for achieving ceramic heat engine components having long lifetimes when subcritical crack growth occurs. Long lifetimes can also be achieved under the same set of conditions (i.e., active subcritical crack growth) by achieving either very small intrinsic flaw sizes in the material, high K_{IC} values, or both, because these conditions require a longer time for a growing crack initiated at an intrinsic flaw to reach the critical size.

The objective of this program task is (1) by means of analytical and experimental studies, to identify a preferred method or methods for measuring the crack velocity v versus applied stress intensity K for the candidate materials at high temperatures; (2) to perform a series of experimental measurements with identified preferred measurement method(s) to select at least four of the candidate ceramics from program element 1 under appropriate environmental conditions to establish the initial data base for them; and (3) to perform a limited number of crack growth studies for a limited number of the candidate materials under cyclic stress conditions to determine if subcritical crack growth in these materials under cyclic stress is substantially different from crack growth under essentially static stress.

Impact fracture processes on ceramic surfaces. Because the relationship of small flaws to the fracture behavior of structural ceramic heat engine components is critical, it is very important to understand the processes by which particles and other engine components that affect the ceramic surface also affect the reliability or lifetime of the component. The basic issue of interest is how particular surface impact events for a given material change the fracture probability relationships while all other variables are held constant.

The general objective of this program task is to quantify this understanding analytically and experimentally for a limited number of the candidate ceramic materials. The candidate ceramic materials will be selected later.

The work includes identification of at least two surface impact events that are considered of particular concern in the design and reliability of advanced heat engines, with one selected from the gas turbine type and one selected from the adiabatic diesel type. The general nature of the impact events to provide the focus for this work will be selected later, but particle impact on rotors or stators and the impact of the closing of an engine valve on a valve seat are examples to be considered.

B.3.3.5 Subelement 3.5—nondestructive evaluation techniques for ceramics

Because of the general lack of plastic deformation energy-absorbing mechanisms, such as dislocation production and movement mechanisms in ceramic materials, the critical flaw or crack size, which results in catastrophic fracture, is very small compared with that in alloys. Therefore, the intrinsic flaw sizes, which ideally should be detectable by NDE techniques in dense-sintered ceramics, should be substantially smaller than the current sensitivity of 50 to 150 μm and preferably less than 10 μm. Most of the NDE on structural ceramics conducted to date in various heat engine programs and elsewhere has been concerned with achieving detection and resolution for these small flaws. There have been several problems in this quest. The problem has not yet been satisfactorily solved for any of the generic monolithic ceramics cited in program element 1.

The goal of any NDE technique for dense ceramic engine components is to identify the spatial location of all flaws within the volume of the part and to measure the sizes and anisotropy of these flaws so that the frequency and location of the largest and therefore most critical flaws are obtained with high accuracy. In addition, this process must be achievable in times that make the technique economical in the context of engine component manufacture. None of the NDE techniques now available satisfy all these criteria.

Another potentially important area for the application of NDE techniques to structural ceramics is green-state ceramics. For the monolithic, composite, and silicate ceramics and others, much of the microstructural configuration that ultimately results in the characteristic flaw population of the dense material is produced during the course of transforming the powders (and fibers) into the green-state body. These undesirable configurations include such things as powder agglomerates, macropores, and fiber clusters, whose rapid detectability by NDE techniques could assist invaluably in fabrication process control and in improving the economics of ceramic engine component manufacture, because potentially defective parts could be identified before high-temperature processing and other expensive operations were applied to the parts. Few, if any, really satisfactory NDE techniques have been demonstrated for green-state ceramics. These materials are much less amenable to propagation and scattering of acoustic waves than are dense ceramics; other means of probing the material volume for discontinuities may be more attractive, such as x-radiography. Major effort within this subelement is directed to the identification and demonstration of NDE techniques capable of indicating both the size and location of discontinuities (flaws) in a variety of green-state ceramics, including injection-molded, injection-molded with binder-removed, slip-cast, slip-cast with binder-removed, and other green states for at least two model materials selected from the group cited in program element 1.

The work in this subelement is organized into four tasks as shown in Fig. B.12: process monitoring, property correlations, component qualifications, and material degradation.

Process monitoring. This program task includes identification of NDE techniques appropriate to determining both the location and magnitude of density variations and other discontinuities in green-state ceramics and the demonstration of those techniques for a selected variety of structural ceramic materials fabricated in the green state by a selection of processes.

The approach includes identification of NDE probes potentially suitable for this purpose, such as x rays and acoustic waves, followed by their application to a statistically designed experiment including fabricated green-state specimens, the destructive examination of some of these green-state specimens, densification of the remainder of the green-state specimens, and NDE and destructive fracture and examination of the dense specimens.

Property correlations. This program task includes experimental activities organized to (1) identify and demonstrate NDE techniques that can unequivocably identify the position coordinates and the quality of flaws within the volume of relatively simple geometry ceramic specimens and (2) seek correlations between the NDE results for these specimens and their fracture behavior.

The ceramic materials for this task will be selected later but will include at least three major types of ceramic materials referenced in program element 1, for which subcritical crack growth is demonstrated in subelement 2, environmental effects, of program element 3.

Component qualification. This program task involves either simulated or actual engine components, employs the high-resolution NDE techniques demonstrated for application to simple ceramic specimen shapes in tasks 1 and 2, and includes the application of these techniques to shapes appropriate to actual engine components.

A major objective of the work in component qualification is to address the issue of complex component shapes, and, if this geometry problem is properly solved, to apply the best identified NDE techniques to statistically significant populations of simulated or actual engine components, followed by destructive testing of those populations to determine the correlation factors for NDE predictions versus actual fracture results.

This work is conducted to demonstrate that one or a combination of high-resolution NDE techniques can be applied to complex heat engine component geometries and can consistently identify the spatial location of the critical flaw (largest flaw) within the candidate component geometries. Success in this endeavor will demonstrate the ability of advanced NDE techniques to qualify a particular component as to its probability of fracture, based on the NDE results and the calculated stress distribution within the component during engine service.

Material degradation. This program task is organized into two parts: the use of NDE techniques to detect and follow the degradation of structural ceramic materials during long-term high-temperature exposure in the presence of stress and active atmospheres and the use of these techniques to detect and quantify degradation in structural ceramics as a function of surface damage at lower temperatures, including those applicable to bearing and other rubbing and/or rolling contact conditions in advanced heat engines.

The first part of this task is an extension of the more exploratory work described previously for the process monitoring task of this subelement. The second part of this task includes the application of high-resolution NDE techniques to selected structural ceramics from program element 1 to detecting surface damage in the ceramic materials in rolling and rubbing contact configurations representing conditions in bearing and sliding contact applications.

Appendix C

DETAILED RESOURCE REQUIREMENTS BY MAJOR PROGRAM ELEMENTS (PERSON YEARS)

The resources required to implement fully the priority tasks detailed in Appendix B were estimated on the basis of the number of research personnel required to achieve the goals of individual tasks on a critical path schedule. A summary of these resources by work element and major task area for each year of the proposed program is given in Table C.1. This summary combines the number of technical and technical support people required in industrial, government, and university laboratories to accomplish each subtask and material listed in the work breakdown structure.

Table C.1. Resource requirements for Ceramic Technology for Advanced Heat Engines Program

(Entire work breakdown structure)

Work element and subelement	Research and technical support (person years)					
	Program year					Five-year total
	1	2	3	4	5	
1. Materials and processing						
1.1 Monolithics	40	66	61	52	35	254
1.2 Ceramic composites	10	17	35	36	26	124
1.3 Thermal and wear coatings	5	11	13	18	12	59
1.4 Joining	6	15	15	12	5	53
Subtotal	61	109	124	118	78	490
2. Design methodology						
2.1 Modeling	2	8	6	4	3	23
2.2 Contact interfaces	12	20	30	20	10	92
2.3 New concepts	4	9	6	4	2	25
Subtotal	18	37	42	28	15	140
3. Data base and life prediction						
3.1 Structural qualification	2	5	6	6	6	25
3.2 Time-dependent behavior	8	15	20	20	18	81
3.3 Environmental effects	4	19	20	23	15	81
3.4 Fracture mechanics	3	5	9	5	3	25
3.5 Nondestructive evaluation	3	5	5	7	8	28
Subtotal	20	49	60	61	50	240
Total	99	195	226	207	143	870

65

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Mr. MCCURDY. This year in the authorization cycle, we have a request that we have both 1988 and 1989 numbers and DOD did that. Have you submitted your 1989 request?

Miss FITZPATRICK. No, sir; we have not.

Mr. MCCURDY. Do you have any—no submissions to OMB or—

Miss FITZPATRICK. No. Under normal schedule, we would make a submission to OMB in September of this year for FY 1989.

Mr. MCCURDY. One document we have asked for, a run out cost through—FY 1988 through 1992, just a general summary. It appears to be a fairly even kind of level budget projection. Is that generally what you are thinking or expecting or——

Miss FITZPATRICK. Or hoping. Yes, sir.

Mr. MCCURDY. It's kind of an ambitious hope, but it's a hope.

Okay. Are there questions from the Subcommittee? Mr. Hayes.

Mr. HAYES. I guess I should in a way of apology to Miss Fitzpatrick, tell her that I have received letters in frustration from constituents and I guess sometimes the same frustration of knowing what I know and coming from where I come in energy policy take that out sometimes on the people who have to listen to it and can't yell back, so instead I'll invite you in the hall to yell back. It seems only fair.

I guess what I was trying to say earlier is this; I sit and listen to people coming from the military with extraordinary confidence that money will develop technology, to the point of testifying that if you put the money in place, we simply will develop the technology for weapons systems. Yet in energy research, it seems to be just the opposite. It seems to me a compelling goal but also a rejection of technology, almost saying it doesn't matter how much money you spend, we're not seeking very much.

It occurs to me that speaking against my own home district's interest, not for it, speaking against it, we have got to prepare ourselves now for alternative fuel uses, and that if we had that same confidence that funding would develop technology, that so many of those in the military have, you should be asking for substantially more money, not substantially less, and that if I'm to believe that Star Wars technology coming from one hand of Government has any credibility, then I certainly have to believe that energy research at any legitimate funding level could advance the society tremendously and protect us from what I believe to be a greater threat to this country then any military action.

I just can't understand how such different philosophies co-exist in the same Government, and the frustration of that causes me to ask things in probably a less common and polite manner than I ought to, but that's where I'm coming from. That's a question that I just think ought to be directed at an overview of Government.

Miss FITZPATRICK. Well, Mr. Hayes, I very much appreciate your sentiments on every point and I share your frustration often. We all struggle with the priorities. We here in the Office of Conservation try to make our best recommendations. That's the best we can do.

Mr. MCCURDY. I think the gentleman makes a very eloquent statement and certainly he's not your typical freshman member and he is going to be a very valuable member of this Subcommittee and I appreciate what he says.

I think the bottom line, too, is that we may yell at you but we expect you to turn around and yell back in your own shop.

Miss FITZPATRICK. I have two heads, Mr. Chairman.

Mr. MCCURDY. We want you to continue that message that there is concern and support on the Hill for these programs and we do not see them as being a waste of money and again, as I said earlier, we are talking about a budget that has, I think, very real potential and yet we don't even round off to those small numbers in DOD, and that's a crying shame. That's a crying shame.

Well, thank you.

Miss FITZPATRICK. Thank you, Mr. Chairman.

Mr. MCCURDY. Our next panel will be an engine panel in effect, with Mr. Harold Helms; Mr. Edwin Strain; Mr. William Powers; and Mr. Noel Nightingale.

Mr. Helms, Chief Engineer of the Vehicular Turbines, Allison Gas Turbine Division, General Motors Corporation. Mr. Strain is Manager of Government Programs, Power Systems, Garrett Turbine Engine Company, the Garrett Corporation. Mr. William Powers, Director of Power Train and Systems Research Laboratory, Ford Motor Company. Mr. Noel Nightingale, Assistant General Manager of the Stirling Engine Systems Division, Mechanical Technology, Inc., Latham, New York.

Mr. HELMS. Mr. Chairman, is it okay if we turn off the lights so we can show our——

Mr. MCCURDY. Yes, let's dim those. First of all, welcome gentlemen. We are pleased to have you here today. Mr. Helms, we especially thank you for bringing the Chevrolet Express automobile. That was very interesting for us to see. I'll take a blue one and I think Mr. Hayes would like a red one. We certainly are delighted to have that presentation today.

Mr. Helms, if you want to proceed, and then we will just move to Mr. Strain, Mr. Powers, and Mr. Nightingale.

Mr. HELMS. Very good. We'll try to get one of those for you in a year or two, maybe for $18,000 or $20,000, something like that; how's that?

Mr. MCCURDY. That would be a sale.

Mr. HELMS. We are very pleased we could bring those vehicles.

STATEMENTS OF HAROLD E. HELMS, CHIEF ENGINEER, VEHICULAR TURBINES, ALLISON GAS TURBINE DIVISION, POWER PRODUCTS GROUP, GENERAL MOTORS CORP.; EDWIN STRAIN, MANAGER OF GOVERNMENT PROGRAMS, POWER SYSTEMS, GARRETT TURBINE ENGINE CO., THE GARRETT CORP., ACCOMPANIED BY DAN KREINER, PROJECT MANAGER FOR AGT AND ATTAP PROGRAMS; WILLIAM F. POWERS, DIRECTOR, POWER TRAIN AND SYSTEMS RESEARCH LABORATORY, FORD MOTOR CO.; AND NOEL NIGHTINGALE, ASSISTANT GENERAL MANAGER, STIRLING ENGINE SYSTEMS DIVISION, MECHANICAL TECHNOLOGY, INC., ACCOMPANIED BY GREG GUTGSELL, JOHN DEERE CO.

Mr. HELMS. Thank you for hearing our testimony today. I'm to report on the current program which we have, which is called our advanced gas turbine technology project. Your letter of invitation

suggested that I comment on the forthcoming program, which is called ATTAP, advanced turbine technology applications program.

I have a slide or two on the Chevrolet express vehicle which you saw outside. Sandy, let's start with the advanced gas turbine technology project.

[Slide.]

Mr. HELMS. We show in this first slide a picture of the engine which we call the AGT 100, a device which we designed for a 3,000 pound vehicle. The intent there was to have the capability at the finish of the program to hit 42.5 miles per gallon, also to meet the emissions standards that the Government has set, also to meet multi-fuel capability. I hope to demonstrate to you that we have met some of those goals, not all of them, in our program to date.

That engine, of course, gets to the kind of performance level that is suggested by helping to evolve the structural ceramics technology area and without that structural ceramics technology, we cannot begin to approach the kind of fuel economy that we show there.

The next chart, please, Sandy.

[Slide.]

Mr. HELMS. Here we show a schedule and you can see by that schedule that we are approaching the end of this project. The project is now scheduled to end the 1st of July of this year. We show down in the lower righthand corner a line which is called ATTAP, which is the follow-on program that's recommended for the fiscal year 1988 budget.

In this program, however, that we have had to date, we are pretty pleased with a lot of the accomplishments, not so pleased with some of the other accomplishments. Actually, you can see that we call for the development of turbine and compressors, the combustor and the regenerator. Those are basic components that are inherent in the engine and involve basically aerodynamics which we now somewhat understand.

I think we could all stand to have a shot in the arm on the size of components that we have here compared to other turbine engines, but basically we have met many of our performance objectives for the turbines, the compressor, the regenerator and the combustor.

The area of still great high risk and significant concern is the ceramics development line at the top of that chart. While we've come a long way, we've a long way to go, and we will look at that in a little more detail as we go along.

I would compliment the Department of Energy, the NASA and the Congress for funding this kind of effort. We believe this is a revolutionary breakthrough kind of technology which will enhance all of the U.S. industry by its future applications to heat engines.

The next chart, please, Sandy.

[Slide.]

Mr. HELMS. Let's look for just a moment at a few of the technologies involved. Here on this chart I've attempted to show the work we have done with combustion. One of the beauties of the gas turbine is that it burns very well, most any form of hydrocarbon fuel, whether it be gaseous, liquid or solid.

On this chart, we've attempted to plot the NOX and the carbon monoxide, two key pollutants, as we think about environmental responsibility today.

You can see that we have labeled AGT 100 goals on that chart and we have a couple of lines shown which call out the diesel and jet engine fuels. That's diesel fuel No. 2 and JP-5, and you will note that the NOX that we have produced in our combustor rig, in this combustor test program, is well below the big bar that you see on the right, which is labeled the diffusion flame combustors. Now, most of the turbine engines that run today have a diffusion flame type combustor. It would be at the edge of the pollution limits that the EPA standards call for.

You can see that the diesel and the jet fuel are well within the limits but there is also a line there that is called methanol. Now, that methanol line is an order of magnitude lower than the other lines and it's a very neat level of pollution capability to have in any heat engine.

The other fuel that we have tested is coal, and the next chart, please, Sandy.

[Slide.]

Mr. HELMS. Shows the picture of the Cadillac that sits at the front of the horseshoe along with the Chevrolet Express, and that vehicle has a gas turbine that runs on dry micronized coal. We think the only automobile like that in the world probably, nobody else that we know of has demonstrated that you can actually burn clean, dry micronized coal responsibly in a heat engine. We say that we have done it here. The coal that we can get today is not clean enough but if we can clean coal properly, we feel that either in the form of dry micronized coal and/or in the form of coal slurries or maybe methanol coal slurries, can burned in the gas turbine. Certainly that kind of fuel is one of the alternatives that we have as a selective option for the country.

The next chart, please, Sandy.

[Slide.]

Mr. HELMS. Now, in this chart, I've attempted to list some of the benefits offered to the technical community by developing the structural ceramics technology. The high temperature capability is one of those benefits that all of us will benefit from significantly as we do develop and apply structural ceramic components in heat engines.

Today, typical metals that are useful to us, cast irons and steels, those metals actually melt at like 2,200 F. The aluminums melt at like 1,200 degrees F. Some of the ceramics have capability of staying in place and maintaining chemical stability at temperatures in excess of 3,000 degrees F.

Now, you say why is that important? That's important because as we combust hydrocarbon fuels, the combustion really occurs at what we call stoichiometric temperatures which is in excess of 3,000 degrees F. The fuel efficiency then of an engine is established by the amount of cooling you must do to the combusted gas to enable the materials to survive in your engine.

If you only have to cool to 3,000 degrees F., then the heat you throw away to the environment is one level. If you have to cool to 2,000 degrees F., you throw away much more heat. Today in our

typical reciprocating engine in an automobile, we are throwing away over a third of the energy of combustion, through the radiator, because of the temperature limitations of the metals.

Mr. McCURDY. If I may, I have actually written a question here on that very thing. When we developed the M-1 tank and had the turbine engines, many West Germans found that they can't pull up behind a tank on the highway because they were literally melting the paint and the chrome bumpers and everything else as they pulled up behind a tank, they were going up and down the audubon, because the heat was thrown out the rear end.

Mr. HELMS. I would invite you, though, sir, to stand behind the Chevrolet Express down here when it is running and you will see that you can stand that close to it and it's——

Mr. HAYES. I'll operate it if Mr. McCurdy will stand behind it. [Laughter.]

Mr. HELMS. I think Mel will be glad to fire that engine up for you. I think what you observed is a truism that you have to be very careful of your design, your design criteria and your operating cycle. In the tank, I don't believe there was a sincere attempt to control exhaust temperature.

Mr. McCURDY. No; not at all.

Mr. HELMS. Certainly, the thermal efficiency of that engine was far less than the thermal efficiency of the engine we are looking at here. So, it's an interesting point though.

There are other advantages of ceramics and I think the Ford testimony may identify some of those such as friction, et cetera, but these are the key benefits from the ceramics material for the gas turbine.

The next chart, please, Sandy.

[Slide.]

Mr. HELMS. When we started our program and Garrett started theirs, we were told that it was nearly impossible to make some of the shapes that were required for the automotive gas turbine. As you look at this chart, you see all of the ceramic components that have now been made for the AGT 100 engine.

I said we had done well on some parts and not so well on other parts. For example, the big white parts you see up here are the glass ceramics made for us by the Corning Glass Works. Those have worked just beautifully for us in our engine. I feel that we might even consider addressing production with those kinds of components at this time.

Contradictory to that, however, I invite your attention to the rotors that you see. We have attempted time after time after time to achieve durability in our engine performance testing and on our engine and on each occasion, the result has been broken blades in those rotors.

This identifies for us then two or three deficiencies in our own design, in the materials with which we work today, et cetera, and it suggests that we need very badly the follow-on ATTAP program to correct some of the design and materials deficiencies we have in the kind of rotors that we have made to date.

I have to applaud the efforts of the U.S. ceramics industry for the work they have done. Even though we had to be bull headed and insist on their trying to make some of these parts, they have

come through in great shape. The part you have in your hand, I think, is an AGT 101 rotor. I believe they suffer the same kind of blade tip losses we do and I don't want to speak for Ed, of course. It's a common problem.

The combustor that we have in our engine and I think it's in the 101, probably both of these combustors, in the transient operating conditions, tend to manufacture carbon, and these particles of carbon going through that rotor will break those blade tips. We need to have enough toughness in the ceramic material to be able to withstand that kind of impact, and I might add that both Ed and I would love to have more money to spend on developing those damn combustors so they produce less carbon also.

Next chart, please, Sandy.

[Slide.]

Mr. HELMS. Here is a list of the different suppliers with which we have worked. If you counted them up, you would find 20 of those suppliers. You will note at the bottom we have worked with some foreign suppliers as well as U.S. suppliers.

Today, the Kyocera Company and probably NGK are two of the top quality parts makers that we have, but even with their parts we still have problems with in our engines.

The next chart, please, Sandy.

[Slide.]

Mr. HELMS. Here is the key ceramic rotor component. We do not have an automotive gas turbine program that has potential for production unless we solve the problems in this key component, and that is the gasifier turbine rotor in our engine and, of equal importance, the power turbine rotor are probelms in our engine. In a single shaft engine, there's only one such rotor.

This silicon nitride rotor is one made by the Kyocera group out of Japan. We have had our best engine run 100 hours on such a rotor, but again the end result was broken blade tips and loss of power in our engine.

The next chart, please, Sandy.

[Slide.]

Mr. HELMS. As we at General Motors have looked at our task, we look at both the radial inflow and axial turbines. The axial turbine is a common aircraft configuration, but it has also been a common automotive gas turbine geometry. We have the axial type turbine in the Chevrolet Express out here. As we have tested that rotor in ceramics, it also is subjected to the same type of failure, blade tip damage from foreign objects going through the rotor, and we think most of those foreign objects to be carbon produced by the combustion liner.

The next chart, please, Sandy.

[Slide.]

Mr. HELMS. I might add that you will note the thickness difference between the radial inflow turbine and the axial turbine. We believe the axial turbine may be an easier fabricating job, and maybe a configuration that might come to the marketplace earlier than the much thicker radial inflow turbine.

Here we show the stationary parts. I'm very proud of that particular picture because here is the interaction of many, many pieces in the combustor discharge area of the turbine, the highest

temperature part of the turbine, and we have put all those parts together and successfully run those parts for a few hundred hours. We think that is a major accomplishment. I might add the that scroll that you see there, the thing that collects the hot gas, in the upper righthand corner, again was one of the nearly impossible pieces to make, just six or seven short years ago and our ceramics industry has addressed that processing job and has come this far.

Now, I don't think we are home free yet. We have a lot of work to do to improve and get uniform properties, but we have made significant progress. We are very proud of that progress and I think you folks should be, too.

Next chart, please.

[Slide.]

Mr. HELMS. As we have addressed the ceramics, we find that you can go in many directions, and by that I mean you can make what is called a monolithic ceramic piece, like that rotor you have there. That's all one basic ceramic chemical formulation, and that particular one is silicon nitride. We have looked at silicon carbide, again, a unique material.

You can add to these materials those stiffening agents, reinforcing bars or rods, if you please, and in this picture I show you a piece of glass ceramic reinforced with silicon carbide fibers. This particular piece was made for us by the Corning Glass Company. A very unique design. These are short whiskers and you can get long fibers that you can reinforce with the matrix material.

One of the key thrusts that we look for in the ATTAP program is to reinforce or toughen the basic monolithic ceramics with either short fibers, long fibers or what we call particulates, additives which are crack arresters in the basic ceramic materials.

The next chart, please.

[Slide.]

Mr. HELMS. This shows a display of hours that we have achieved in our AGT 100 program, actually the number of hours today is 540 hours. You can see that some of the ceramic components have been tested all the time we have run our engine and some of the parts, we have had trouble getting them qualified to go to the engine.

For example, the rotor test time that you see there is 121 hours. It took until last year to get a rotor qualified through all the spin testing and other testing, qualification testing required, to qualify a piece for test in the engine. However, we think this again is a significant accomplishment. If we had the luck—I shouldn't say it that way—the skill to design with the materials available to us, I would have hoped those hours might have been 2,000 instead of 500 by now, but that's the way it is. We are developing new technologies, plowing new ground, so to speak, in this technology area.

The next chart, please.

[Slide.]

Mr. HELMS. I think one of the blessings that we have in this country right now is we have two teams that have a complete set of tools, facilities and manpower with which to work, the Garrett Company and our General Motors activity.

That's just a list of special testing rigs. You will note that we have a checkmark behind all but two or three of those rigs and they are used to develop ceramics technology specifically for this

kind of engine application. We think it's a capability worth preserving.

Next chart, please.

[Slide.]

Mr. HELMS. The follow-on program that has been discussed with DOE is called ATTAP. As we have discussed it with DOE, we have talked about a five year program, starting this July 1. The objective is to finish the technology development required to have successful ceramic components for automotive gas turbine engines. We have identified certain work items and listed them there as goals on that chart. I will leave that for you to read later. The next chart, please, Sandy.

[Slide.]

Mr. HELMS. We have tried to identify. where we need to concentrate our work relative to components, we certainly have identified the rotor as the number one priority piece. Given unlimited funding, we would probably put more effort on the lower priority items. With the funding that may be available to us, we feel we have to concentrate on the rotor. That is indeed the singular key ceramic component to have a successful engine.

Next chart, please.

[Slide.]

Mr. HELMS. I show this list of candidate materials just to illustrate the point to your folks that we are looking at many materials. I don't propose that is a complete list of materials but as we talk to new people that are becoming interested in making ceramic components, such as Alcoa, such as the Dow Corning people and others, that list is growing day by day. The next chart, please.

[Slide.]

Mr. HELMS. Now, that's just a brief look at the ATTAP program. I feel the ATTAP program is a key development for us to proceed with in this country.

As you look down the road and say what can we do in the future, the Chevrolet Express is one of the possible vehicles that may be with us in the future. The particular vehicle you see here is a research vehicle, pure and simple. We think to ourselves that we have come so far in the past years as we look ahead, we can see high speed land travel as one of the possible transportation modes. This may be a candidate vehicle for high speed land travel in the future. The next chart, please, Sandy, will identify many of the key technology areas that are incorporated in this vehicle.

[Slide.]

Mr. HELMS. I invite you to read over that list of advanced technologies. They fall into four general categories and those are unique aerodynamics, the integrated electronic control system, which leads to a drive by wire type system; advanced materials and they are very specific unique materials that are applied in that vehicle, and perhaps it is worthy of mentioning that the skin on that vehicle is a polymer composite skin reinforced with graphite fibers and kelvar fibers.

The turbine that is in the vehicle that sits on the curb out there (Chevrolet Express) has metal components. With ceramic components, we can achieve the kind of fuel economy that is mentioned

in that brochure that I think each of you gentlemen have seen by now.

The other things that are on that list are all very important and sitting in the room here today are real experts that have developed that particular vehicle.

We feel by reaching out and looking at those kinds of vehicles that we feel are candidates for the future, we can solve today problems we may be faced with tomorrow as we address future transportation systems.

This is a research vehicle. It is a candidate vehicle to receive and to demonstrate the kind of technology we are developing in the DOE programs. I might add that I feel intense pride that my corporation chooses the turbine as a candidate power plant, an ultimate power plant for the future and with the new technologies that are emerging, I think it may have a good chance of being a real power plant in future vehicles.

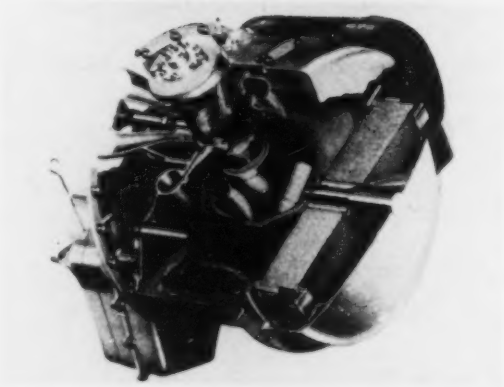
Now, I've said probably more than you have wanted to hear. Thank you for listening so patiently. Later or now, at your choice, I'll answer questions on our testimony.

[The prepared statement of Mr. Helms follows:]

Testimony to the
House Subcommittee on Transportation,
Aviation and Materials
of the
Committee on Science, Space, and Technology
U.S. House of Representatives

3 March 1987

AGT 100



Department of Energy
Advanced Gas Turbine Technology Contract
Advanced Turbine Technology
Applications Program

Harold E. Helms, Chief Engineer

Allison Gas Turbine Division
General Motors Defense Operations Group
General Motors Corporation

Allison GAS TURBINE DIVISION General Motors Corporation

HAROLD E. HELMS
Chief Engineer — Vehicular Turbines

Education

B.S. in Engineering Mechanics, Purdue University, 1948
M.S. in Engineering, Mechanics, Purdue University, 1950

Work History

1952 to Date: Allison Gas Turbine Division
Power Products Group
General Motors Corporation, P.O. Box 420
Indianapolis, Indiana 46206

- Chief Engineer, Advanced Vehicular Engines
- Chief — Regenerator Systems
- Program Manager — NASA QCSEE Program
- Chief — Analytical Mechanics
- Section Head — Stress, Heat Transfer, Vibrations, Weights, and Computers
- Supervisor — Rocket Nozzles and Cases
- Deputy Leader — Allison/Rolls Royce Joint Project
- Senior Project Engineer — T40 Engines, T56 Engines

1950 to 1952: Engineer, Argonne National Laboratory, Lemont Illinois

1946 to 1950: Instructor — Advanced Mechanics, Purdue University, West Lafayette, Indiana

Responsibility/Experience

Mr. Helms is responsible for advanced technology vehicular engines at Allison. This responsibility includes the AGT 100 Project — DOE/NASA contract, Fuel Cell Advanced Technology Engine, and Coal Burning Turbines. The AGT 100 Project was planned and is directed under Mr. Helms' leadership. Ceramic materials technology is the major thrust of this program and he is a recognized leader in the application of ceramic components in heat engines.

Analytical Mechanics, including stress analysis, heat transfer, vibrations, weights, and computer analysis, was directed by Mr. Helms. Turbine cooling, including convection, film, and transpiration cooling methods, was implemented and developed under Mr. Helms. Lamilloy, an Allison invention, was conceived and developed under his direction.

Mr. Helms prior experience includes work on rocket motor cases and nozzles and turboprop, turbofan, turboshaft, and turbojet engines at Allison. Mr. Helms also worked on the Atomic Energy Commission reactor project for the Nautilus submarine.

Allison GAS TURBINE DIVISION General Motors Corporation GM

INTRODUCTORY REMARKS

Thank you, Mr. Chairman, for this opportunity to present a status report on the General Motors, Allison Gas Turbine Division "Advanced Gas Turbine Technology Project" (AGTTP). This project is supported by the Department of Energy (DOE) and contracted through the National Aeronautics and Space Administration (NASA) Lewis Research Center. My testimony will also include comments on the "Advanced Technology Turbine Application Program" (ATTAP) and on the General Motors new "Chevrolet Express" research vehicle as requested in your letter of invitation. I am Gene Helms, chief engineer for advanced vehicular engines, and I am responsible for the automotive gas turbine (AGT) work at Allison.

ADVANCED GAS TURBINE TECHNOLOGY PROJECT (AGTTP) OBJECTIVES AND KEY TECHNOLOGIES

The objective of the AGTTP program has been to demonstrate an all-ceramic hot section in the Allison AGT 100 (shown in Figure 1). The *key technology* has been the development of ceramic components that will meet automotive gas turbine requirements. This objective and key technology effort has evolved from the original objectives of 30% improvement in fuel economy over current internal combustion engines, alternate fuel capability, and emissions that would meet 1986 federal emission standards. Initial program goals also included competitive initial and life cycle costs, competitive reliability and performance, and competitive noise and safety characteristics.

AGTTP Schedule

Figure 2 shows the latest schedule for the AGTTP (AGT 100) contract. This shows completion of the contract on 1 July 1987 with a follow-on ATTAP program. Most of the milestones for this program have been successfully achieved. The demonstrations of initial aerodynamic and mechanical components and the AGT 100 system compatibility and component matching are on schedule. More than

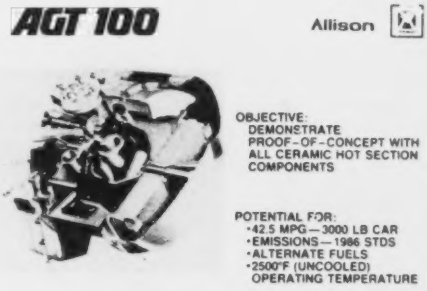


Figure 1. Advanced Gas Turbine Technology Project (AGTTP)

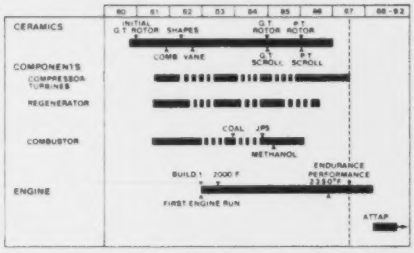


Figure 2. AGT 100 Project Schedule

540 hours of engine testing with ceramic components has revealed both successful results and development problems. For example, multiple fuel testing in a combustion rig and in engines has revealed that emissions with methanol and diesel fuel are far less than with conventional turbine combustion systems (see Figure 3). Over 5400 hours of component rig testing have proven the initial aerodynamic, mechanical, and structural performance of compressor, combustor, turbines, regenerators, gearboxes, shaft systems, seals, and other engine components.

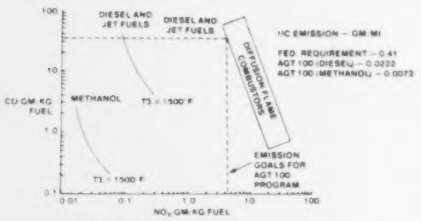


Figure 3. Premixed/Prevaporized AGT 100 Combustor

The 750 engine parts have been designed, fabricated, and tested to establish compatibility over a wide range of conditions including:

- zero to 100 horsepower
- ambient temperature to 2500°F
- subatmospheric pressure to over 70 lb/in.^{2}
- 43,000 rpm to 86,000 rpm engine shaft speeds

Both stationary and rotating ceramic components have been tested in rigs and engines. Many stationary ceramic components have been successfully used in all engine testing to date. These components include combustor parts (liner, dome, rings and pilot tube), regenerator parts (regenerator disk, bulkhead and seals) and various heat barrier rings and piston rings. The ceramic turbine scrolls and associated parts (vanes and backplates) and the gasifier rotors have been tested in the past year. A 100 hour run of a ceramic gasifier turbine rotor, silicon carbide and silicon nitride scroll components, and ceramic composite combustors, and backplates have been operated successfully in the 1986 rig and engine test program. The evident development deficiency is with the ceramic turbine rotors where every engine-tested turbine rotor has failed at times varying from a few minutes to 100 hours. The apparent lack of toughness, lack of metallographic uniformity of grain structure, and the occurrence of too many small structural defects (pores, inclusions, foreign particles, lack of homogeneity) has reduced our ability to achieve desired durability. Development in the forthcoming ATTAP program will focus on this ceramic rotor problem.

Allison has completed initial development of compressor, turbine, and regenerator components for the AGT 100 engine. The AGT 100 combustor has been rig tested with diesel fuel No. 2, JP-5 fuel, and methanol fuel with results exceeding 1986 federal emission standards requirements. A parallel General Motors automotive gas turbine program has demonstrated the combustion of both dry micronized coal and diesel fuel in an automotive gas turbine that has been installed in a 1979 Cadillac Eldorado. These results prove that automotive gas turbines can operate on various alternative fuels.

Overall, the AGTTP program must be considered a significant success because of greatly improved capability in producing ceramic components, including improved yields in batch processing, and because of many successful ceramic component rig and engine test demonstrations by both AGTTP DOE/NASA contractors.

BENEFITS OF CERAMIC COMPONENTS IN AUTOMOTIVE GAS TURBINES

The benefits ceramic materials offer that are of critical importance to automotive gas turbines are shown in Figure 4.

All of these benefits from ceramic materials apply to all heat engines, including automotive gas turbines, and are becoming more important each year. The AGTTP project has been the major U.S. Government/industry program to bring ceramic materials from laboratory status to practical application in the automotive gas turbine. An important feature of the program has been the synergism created between the gas turbines manufacturer, the ceramics industry, and government and private laboratories (such as Oak Ridge). This interactive procedure has greatly enhanced the ability to identify and search for solutions to problems that occur during research on major new technologies such as the high risk structural ceramic components for heat engines involved in AGTTP. This interactive procedure concluding with ceramic component demonstrations in useful engines is a sound and realistic approach to commercialization of these new materials.

- CAPABILITY TO OPERATE AT HIGHER OPERATING GAS TEMPERATURES (500 -700 F) THAN METALS WITHOUT COOLING, YIELDING HIGHER TURBINE EFFICIENCY AND BETTER FUEL ECONOMY
- SUBSTANTIAL POTENTIAL FOR LOWER COST THAN SUPER ALLOY METALS CURRENTLY USED IN AUTOMOTIVE GAS TURBINES
- LESS THAN HALF THE WEIGHT OF METALS YIELDING LOWER INERTIA AND FRICTION FORCES THAT GIVE IMPROVED ACCELERATION AND FUEL ECONOMY
- NO CRITICAL MATERIALS (SUCH AS CHROMIUM, COBALT, NICKEL, MOLYBDENUM, TUNGSTEN) ARE PRESENT IN CERAMICS AS COMPARED TO SUPER ALLOY METALS

Figure 4. Benefits of Structural Ceramics in Heat Engines

AGTTP Ceramic Component Development

Figure 5 shows a montage of ceramic components for the AGT 100 engine. The complexity in rotors and scrolls vividly demonstrates the improved processing capabilities of suppliers. At the beginning of the AGTTP program, all U.S. and foreign ceramic component suppliers considered these shapes to be nearly impossible to fabricate. Now parts are available from both U.S. and foreign ceramic suppliers. It is noteworthy that several of these components have been made and tested from both monolithic (all one chemistry like silicon carbide or silicon nitride) and from fiber reinforced monolithic and glass ceramics. Further, it is expected that particulate reinforced monolithic ceramics will be available before the end of the AGTTP project. It is expected that the application of composite ceramics to the critical turbine rotors will provide one approach for achieving the required toughness in this key ceramic component in the follow-on ATTAP program.

Figure 5. Ceramic Components for AGT 100

CERAMIC COMPONENT SUPPLIERS

In the development of AGTTP ceramic components twenty different suppliers of ceramic component technology have been used by Allison. These suppliers are shown in Figure 6. It is noted that only U.S. suppliers have received government-supplied funds for evolving new processing, new materials chemistry, and special tooling to produce parts. It is also noted that both monolithic and ceramic composite materials have been pursued in the Allison program. Sohio, GTE, Norton, and Corning Glass Works have received the majority of the ceramic component research funds and are to be applauded for the tremendous advances they have made in the ability to form extremely intricate shapes. They have also made significant contributions to basic processing, nondestructive testing, and process yields. In addition, they have expanded communication and technology exchange within the U.S. technical community.

Simultaneously, a new supporting technology for basic ceramic materials is beginning to evolve from the DOE Ceramic Materials Project (CTP) being funded through Oak Ridge and supplementary research funded through NASA. Materials evolving

U.S. SUPPLIERS WHO RECEIVED DEVELOPMENT MONEY AND PARTS BUY MONEY
- SOHIO
- GTE
- CORNING GLASS (MONOLITHIC AND COMPOSITES)
- NORTON

U.S. SUPPLIERS WHO RECEIVED PARTS BUY OR TESTING MONEY
- COORS PORCELAIN
- PURE CARBON
- OAK RIDGE
- A-HAUS
- AMERICON (COMPOSITE)
- C-CAT (COMPOSITE)
- ATLAS
- SRI
- 3M COMPANY
- A.C. SPARK PLUG
- BUHLEN
- BATTILLE

FOREIGN SUPPLIERS WHO RECEIVED PARTS BUY MONEY
- KYOCERA
- NGK
- SEP (COMPOSITE)
- ASAHI GLASS
- FELDMUHLE
- ASEA

Figure 6. AGTTP Ceramic Materials Suppliers

from these basic programs will contribute heavily to future U.S. ceramic component developments. Further, the new DOE-sponsored Oak Ridge High Temperature Materials Laboratory adds a new level of instrumentation, skilled personnel, and a multitude of unique approaches for new materials, materials characterization, and data base generation for ceramic components for heat engine applications.

AGTTP 1986 COMPONENT EVALUATION HIGHLIGHTS

Figure 7 shows an AGT 100 radial inflow silicon nitride rotor. This rotor is the current state of the art and represents over 260 rotor spin tests, many engine builds, and the expenditure of over eight million dollars. In 1986, a rotor like that shown in Figure 7 achieved 100 hours of testing in the AGT 100 engine. The climax of this test was foreign object damage of the blade tips. This was the result of excess carbon that formed in the combustor due to incomplete combustion of the fuel during transient engine operation. Many other silicon nitride and silicon carbide rotors have been tested with similar results. Corrective action includes improved combustion during transient operation, improved structural design of the rotors, and improved properties of the materials used for rotors. Of these three actions, two are to be accomplished at Allison and the other, improved material properties, must be accomplished by the ceramic component suppliers. While the rotor success that has been achieved is less than desired, progress has been demonstrated in parts fabrication capability. This is a major breakthrough. Unfortunately, only two suppliers (one in the U.S. and one foreign) have been able to provide rotors worthy of engine testing to date. It is encouraging that two additional U.S. suppliers may possess the equipment, manpower, and dedication to produce rotors in the near future.

Figure 8 shows an axial turbine rotor produced in the U.S. for the General Motors AGT-5 engine that

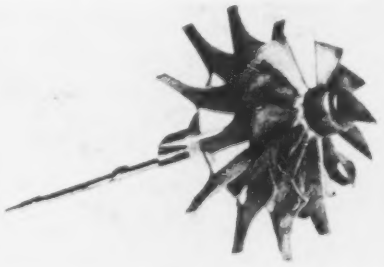


Figure 7. Silicon Nitride Gasifier Rotor

will be shown in the new Chevrolet Express research vehicle. The evident difference in thickness between the axial and radial turbine rotors makes the axial rotor more producable, lighter-weight, and less costly. Testing of this rotor has also revealed foreign object damage on blade tips, suggesting the same development actions are required as with radial inflow turbines.

Figure 9 shows the AGT 100 gasifier turbine scroll, vane, and backplate parts successfully tested in 1986. The successful testing with both U.S. and foreign made parts is particularly noteworthy because of the shape of the scroll, the number of parts in one full scroll assembly, and the severity of the thermal environment out of the combustor and into the turbine. Sohio, Norton, GTE, and Kyocera parts are involved in these stationary engine components. The reaction bonded silicon carbide scroll has been in rig tests (for qualification to go to the engine) and four engine builds. This is significant performance for such complex parts. We note that all 540 engine hours of AGT 100 testing have been achieved with Sohio silicon carbide combustor parts and Corning aluminum silicate regenerators and Corning lithium-aluminum-silicate regenerator bulkheads.

Figure 8. Ceramic Rotor — Axial

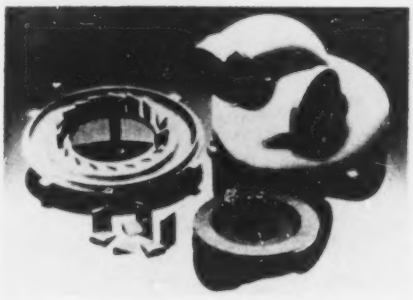


Figure 9. Carborundum Silicon Carbide Stationary Parts

Figure 10 shows a new (1986) kind of material that was made by Corning for the AGT 100 gasifier turbine backplate. The silicon carbide whiskers are randomly distributed in a glass ceramics matrix consisting of magnesium, aluminum, and silicate (MAS). This new geometry and chemistry represents a three fold improvement in strength and a three fold improvement in toughness as compared to the original MAS matrix material. We believe this level of improvement in material properties is the kind of change required to achieve successful automotive gas turbine rotors. Again, this component was successfully engine tested in the AGT 100 program in 1986.

Figure 11 is a summary of accumulated test hours on the AGT 100 ceramic components at the middle

CORNING SiC WHISKER COMPOSITE BACKPLATE
• CORNING MAS GLASS CERAMIC MATRIX
• ARCO SILAR SC-9 SiC WHISKERS (25 v-o)
• STRENGTH 50-60 KSI
• FRACTURE TOUGHNESS (K_Ic) 5-6 KSI √IN

Figure 10. Ceramic Component Development

of January 1987. This engine testing is further complemented by over 5400 hours of rig testing of many components. In 1986, for example, a combustor rig test of a silicon carbide fiber reinforced silicon carbide combustor received over 20 hours of rig evaluation at temperatures up to 2400 F.

Figure 12 shows a list of AGT 100 rigs and engines that have contributed to the technologies put in place by the AGTTP program. This represents a unique facilities capability shared only by Garrett Turbine Engine Company with their AGT 101 engine. It is noted that two very unique teams of experts in the development of ceramic components exist in the United States today. These two teams

	CERAMIC COMPONENT	ENGINE TEST TIME (HRS) HIGH TIME PART	TOTAL TIME
COMBUSTOR	DOME	153	409
	BODY	214	517
	PILOT TUBE	123	517
	DILUTION BAND	247	517
TURBINE	VANE	71	157
	ROTOR	100	121
	SCROLL	21	48
	INNER BACKPLATE	53	97
	OUTER BACKPLATE	20	48
REGENERATOR	DISK	271	517
	BULKHEAD	149	517
MISC	SHIM GAS TURB	126	517
	SHIM PWR TURB	126	517

Figure 11. Ceramic Component Operating Time

have been established by the excellent DOE and NASA sponsored AGTTP programs.

ADVANCED TURBINE TECHNOLOGY APPLICATIONS PROGRAM (ATTAP)

The DOE-sponsored AGTTP project has shown that additional ceramic material and ceramic component capability must be established to provide a technology base that will enable U.S. industry to achieve the successful application of ceramic components in automotive gas turbines. To expedite the goal of early use of ceramic materials in automotive gas turbine engines, the planned ATTAP program should be implemented in FY 87. Figure 13 shows an Allison-stated ATTAP objective and goals.

In 1984, DOE and NASA established the Ceramics Technology Program (CTP) through many contracts to U.S. industry, universities, and government laboratories. New materials and design concepts are expected to emerge from this joint effort from Oak Ridge National Laboratory (ORNL) and NASA. These new technologies should be integrated into the ATTAP program to help expedite the achievement of the ATTAP objectives. This will require coordination by the ATTAP contractors with the ORNL group and its contractors. In addition, the ATTAP contractors must integrate the results of the CTP activities with credible ceramic suppliers to produce useful ceramic components for the automotive gas turbines. Durability testing of individual components and full engine compliments of ceramic components will finish the demonstration of ceramic material and component technology readiness in the ATTAP program. Allison is prepared to fully cooperate with the other ATTAP contractors, DOE/NASA groups, ORNL contractors in the CTP program and other contributors of ceramic materials technology for the ATTAP program.

	USED FOR CERAMIC TESTING
ENGINES	x
COMBUSTOR RIG	x
TURBINE RIG	
REGENERATOR DISK/SEAL HOT-FLOW RIG	x
STATIC COMPONENTS HOT PROOF RIG	x
TURBINE ROTOR FOD RIG	x
COMPRESSOR RIG	
REGENERATOR CYCLIC THERMAL EXPOSURE RIG	x
ROTORDYNAMICS RIG	
ROTOR COLD SPIN RIGS	x
VANE THERMAL SHOCK RIG	x
BULKHEAD PRESSURE TEST RIG	x
REGENERATOR SEAL LEAF RIG	
REGENERATOR FLOW DISTRIBUTION RIG	x

Figure 12. AGT 100 Evaluation and Development Tools

Allison
GAS TURBINE DIVISION
General Motors Corporation

SCHEDULE

- FIVE YEAR PROGRAM BEGINNING IN FY 87

OBJECTIVE

- ADVANCE THE TECHNOLOGY OF STRUCTURAL CERAMIC COMPONENTS TO SATISFY REQUIREMENTS FOR FUTURE AUTOMOTIVE GAS TURBINE ENGINES

GOALS

- EXPAND AND IMPROVE ANALYTICAL TOOLS NEEDED BY ENGINE AND CERAMIC SUPPLIER INDUSTRIES IN THE U.S.
- DEVELOP NEW AND IMPROVED MONOLITHIC AND CERAMIC COMPOSITE MATERIALS AND IMPROVED DESIGNS TO ACHIEVE SUCCESSFUL CERAMIC COMPONENTS FOR EXISTING U.S. AGT TEST ENGINES
- COORDINATE MATERIALS RESEARCH TECHNOLOGY PROJECTS (DOE/NASA/ORNL), CERAMIC SUPPLIER DEVELOPMENTS, AND ATTAP ENGINE CONTRACTOR EFFORTS TO ACHIEVE SYNERGISTIC RESULTS ON AUTOMOTIVE GAS TURBINE CERAMIC COMPONENTS
- EVALUATE RELIABILITY/DURABILITY OF IMPROVED CERAMIC COMPONENTS IN RIGS/ENGINES FROM AGT PROJECTS

Figure 13. ATTAP Program — Allison

ATTAP Emphasis and Priorities

Emphasis in ATTAP must necessarily be focused on the highly stressed, high temperature turbine wheels. The turbine vanes, scrolls, combustor, and regenerators will receive less emphasis although each of these components requires additional development before full technology readiness is demonstrated in the automotive gas turbine test engines. Figure 14 shows the priorities assigned for the ATTAP test engine ceramic components.

The extent of funding available, the degree of success achieved on the top priority components, and the emergence of new technologies for each type of component will largely determine the level of effort applied to the various components shown in Figure 14.

ATTAP Candidate Materials

Figure 15 shows a list of some of the materials and/or improvements proposed for ATTAP by current ceramic suppliers. It is believed that materials improvements, improved rotor and other component designs, cooperative efforts with the U.S. ceramics technical community, and continued judicious use of existing manpower and facilities now in place will lead to the successful achievement of ATTAP program objectives for high temperature structural ceramics materials.

Chevrolet Express Research Vehicle

General Motors has maintained a continuous interest in automotive gas turbines since 1950 and has built many research and development vehicles to evaluate this alternate powerplant for potential use in a variety of products produced by the Corporation. These include passenger cars, heavy duty vehicles (trucks, buses, road building equipment), locomotives, power generation equipment, and military equipment.

The latest General Motors research vehicle, powered by a gas turbine, is the "Chevrolet Express". Figure 16 shows a cut-a-way view of this vehicle that could be an integral part of a new transportation system concept for high speed land travel between major cities in the United States. The evolving definition of the system has suggested a vehicle with 150 miles per hour capability and the Chevrolet Express is an initial attempt to add to the engineering data base for continued assessment of high speed vehicles systems. The gas turbine powertrain system provides a 25 miles per gallon capability at this 150 miles per hour operating condition. This vehicle,

has many innovative and exciting applications of new technologies, and some of these are listed in Figure 17.

In the future, new technology that becomes available from the AGTTP and ATTAP programs may be demonstrated in this kind of car.

MUST PRIORITY	–	TURBINE ROTORS
SECOND PRIORITY	–	TURBINE VANES TURBINE SCROLLS REGENERATORS
THIRD PRIORITY	–	TURBINE COMBUSTORS BULKHEADS BACKPLATES THERMAL BARRIER PARTS ABRADABLE COATINGS SEALS

Figure 14. Test Engine Component Priorities

MONOLITHIC CERAMICS
- SILICON CARBIDE (SiC)
- SILICON NITRIDE (Si_3N_4)
- GLASS CERAMICS (MAS, LAS, CAS, ETC.)

COMPOSITE CERAMICS
- SiC FIBER REINFORCED SiC
- SiC FIBER REINFORCED Si_3N_4
- Al_2O_3 FIBER REINFORCED Si_3N_4 AND SiC
- PARTICULATE REINFORCED SiC AND Si_3N_4
- SiC AND Al_2O_3 FIBER REINFORCED GLASS CERAMICS
- NEW FIBERS

IMPROVED POWDERS FOR SINTERING

IMPROVED CERAMIC COMPONENT PROCESSING COST REDUCTION

Figure 15. Material Candidates for ATTAP

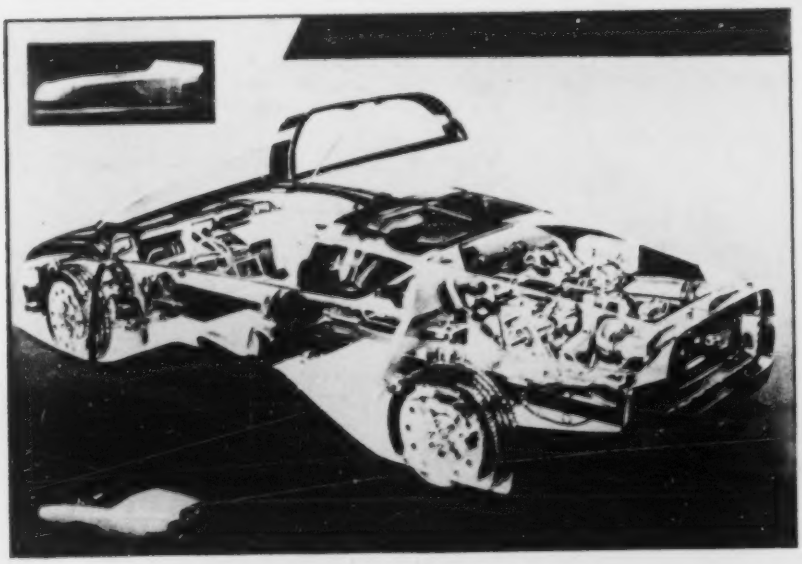


Figure 16. Chevrolet Express

CHEVROLET EXPRESS

UNIQUE AERODYNAMICS
- DRAG COEFFICIENT (.195 – .34 TYPICAL NOW)
- POSITIVE DOWN FORCE
- SHAPED UNDERBODY – REAR DIFFUSER
- ENCLOSED WHEELS
- RETRACTABLE WINDSHIELD WIPER – NO EXTERNAL HANDLES

INTEGRATED ELECTRONIC CONTROLS
- VECTOR-GRAPHICS NAVIGATION SYSTEM
- DRIVE BY WIRE
- REAR TV IMAGES
- VEHICLE SPACING ON THE ROAD
- VARIABLE RIDE HEIGHT CONTROL
- ELECTRONIC POWER STEERING
- THROTTLE CONTROL – CRUISE CONTROL
- COLOR CRT DATA DISPLAY
- ELECTRONIC ENTERTAINMENT

ADVANCED MATERIALS
- FUTURE CERAMIC ENGINE PARTS
- POLYMER COMPOSITE BODY SHELL
- STEEL SPACE FRAME
- CENTRALLY LOCATED PLASTIC FUEL TANK
- INTEGRATED POLYMER COMPOSITE SPRINGS – SHOCKS
- HIGH SPEED GOODYEAR TIRES

ADVANCED TURBINE POWERTRAIN
- CONSTANT SPEED – HIGH TORQUE
- MIDSHIP ENGINE MOUNT
- REAR EXHAUST
- LOW FRICTION
- EXHAUST HEAT RECOVERY
- LOW NOISE – VIBRATION

Figure 17. New Vehicle Technologies

RECOMMENDATIONS

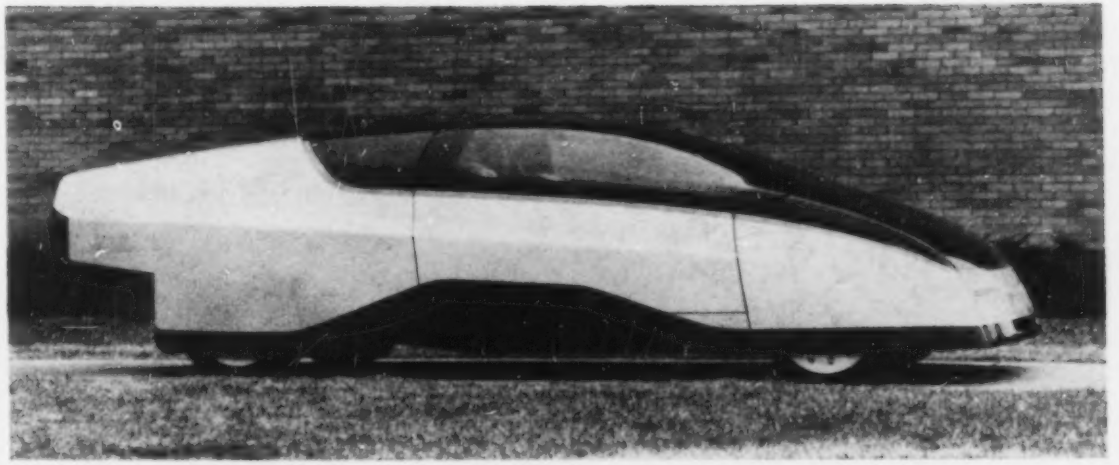
The new DOE ATTAP program requires significant levels of effort in:

- component design and analysis
- materials development (at ceramic component suppliers) and characterization (at ATTAP contractor facilities)
- component fabrication (suppliers-contractors)
- component evaluation and proof testing
- technology verification in automotive gas turbines

Because of the wide range of these activities, *we recommend* that ATTAP funding be established at least at current levels for FY 88.

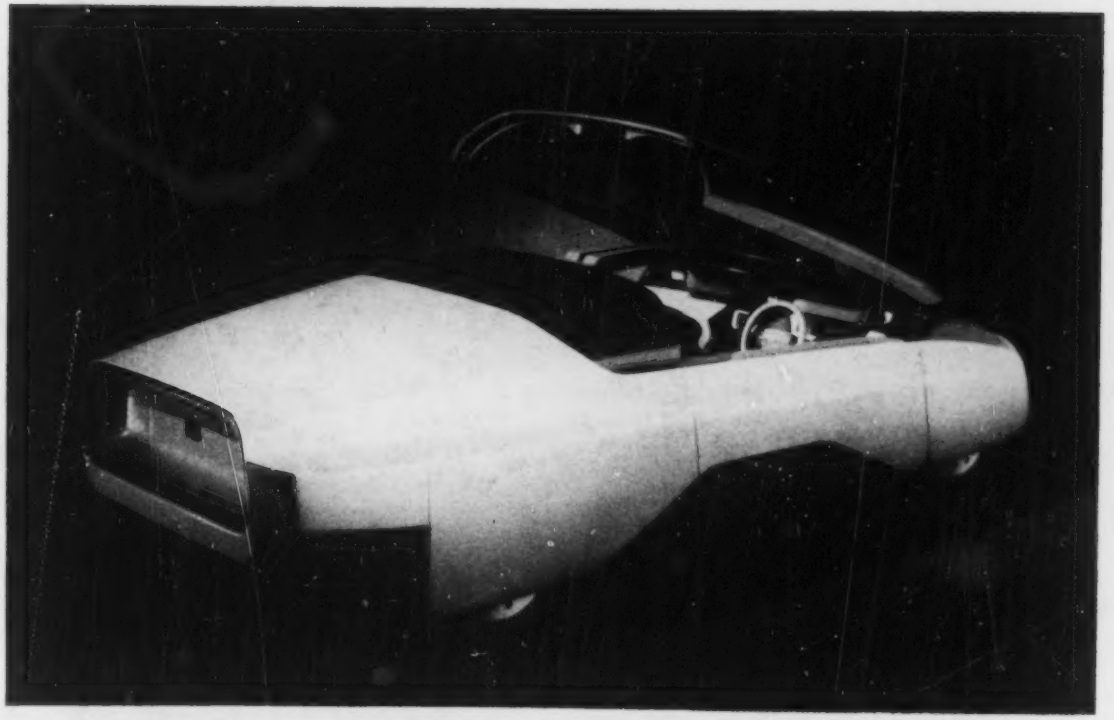
We believe that advanced structural ceramic component technologies for heat engines is one of the high risk advanced areas where government support is needed and where the U.S. will benefit by achieving and maintaining world leadership in both ceramics and future heat engine applications.

Mr. Chairman, this concludes my prepared remarks. Thank you again for this opportunity to present information which may help the committee. I will be pleased to answer questions or further discuss topics in my testimony.



CHEVROLET EXPRESS . . . is a streamlined, whisper-quiet, turbine-powered, ground-hugging, four-passenger, 150-mile-per-hour, futuristic highway alternative to the hassle of short-distance air travel. Aerodynamically efficient design helps Chevrolet Express achieve high speed performance and high fuel economy — usually mutually exclusive vehicle characteristics. A fully enclosed underpan makes the Express "slipperier" than conventional vehicles because individual components are not exposed beneath the car, but the vehicle's mid-mounted engine and central fuel system allow easy access to exhaust, fuel and driveline systems for servicing. These characteristics help create a drag coefficient of 0.195 for the Express, which is lower than the engineers' goal of 0.200.

CHEVROLET PUBLIC RELATIONS CENTRAL OFFICE WARREN, MICHIGAN 48090



CHEVROLET EXPRESS . . . is a streamlined, whisper-quiet, turbined-powered, ground-hugging, four-passenger, 150-mile-per-hour, futuristic alternative to the hassle of short-distance air travel. Structural advances made on the Express include a one-piece front-hinged canopy and retractable windshield wiper system, two reasons why Express has a drag coefficient of 0.195. All major exterior body panels, except the hood and engine cover, are graphite-reinforced plastic. Passenger and engine compartments consist of a cage formed by a graphite fiber-reinforced resin floor pan bonded to a steel space-frame. The cage and the frame ride atop a "backbone" frame fitted with the fuel system, front and rear suspension systems and drivetrain.

CHEVROLET PUBLIC RELATIONS CENTRAL OFFICE WARREN, MICHIGAN 48090

Mr. McCURDY. Thank you very much, Mr. Helms. That was very interesting and certainly a fascinating presentation.

Mr. Strain.

Mr. STRAIN. Assisting me today is Mr. Dan Kreiner who is the Project Manager for the AGT and the ATTAP programs at Garrett. Garrett is one of the Allied-Signal companies, Garrett Turbine Engine Company is one of the divisions of Garrett as shown on this chart.

[Slide.]

Mr. STRAIN. Garrett has been working on the AGT 101 under contract to DOE and NASA since October, 1979. Garrett is the prime contractor. Major subcontractors supporting us in the program have been Ford, SOHIO, Corning Glass Company, AiResearch Casting Company and many of the ceramic suppliers that Gene showed on his chart.

The AGT 101 team has been developing high risk, long range technology for advanced gas turbines for future automotive and other power plant uses. Major emphasis of the program has been to develop ceramic component technology for gas turbine engines.

In this testimony, we wish to focus on why this country needs this ceramic technology that has been provided only by the AGT program, and why ceramics need continued U.S. Government support under the ATTAP program.

Why is ceramics important? The constituents for ceramics are readily available in the U.S. in an inexhaustible supply. The need for strategic materials is reduced, many heat engines use strategic materials including the gas turbine. These materials in many cases are provided by foreign sources that are not always available. Therefore, our national security can be impaired.

Ceramics offer the gas turbine better fuel economy, substantially lower cost potential, adequate raw materials for mass production.

Why has the AGT program been important? The AGT program has been the only—the major U.S. Government/industry sponsored program devoted to moving the focus of ceramics from the research laboratories to a practical application to the automotive gas turbine engine.

The AGT program has been the only one in the U.S. that has allowed an all ceramic engine hot section to be designed from inception. This is the AGT 101. The tan parts are the ceramic parts in this engine.

[Slide.]

Mr. STRAIN. On the next chart, the ceramic parts are also displayed. You will notice in our particular engine, these are all objects of revolution.

The program has allowed ceramics expertise from the auto, gas turbine, ceramics industry and the Government to develop ceramics technology and integrate this technology into the gas turbine operating environment, via test rigs and engine test beds. This is really the only practical approach to successful development of ceramics technology.

The program has allowed the team to advance this long range high risk technology which no individual company could afford. Without the AGT program, ceramics development would take much longer and cost much more. The program has allowed the

U.S. industry to stay competitive with foreign ceramic technology development.

The major AGT 101 accomplishments is shown on this chart.

[Slide.]

Mr. STRAIN. The AGT 101 program is to be completed, as Gene said, by June 30, 1987. The program has successfully demonstrated the feasibility of supplying ceramics to gas turbines. In our particular program, the ceramics structural design approach has been validated with successful proof test of 137 components. We have run our ceramics components over 40 hours at exposure to 2,500 degrees F. We have operated our ceramics turbines successfully to 100,000 rpm in the ceramic engines. We have tested a ceramic engine for 85 continuous hours at 2,200 degrees F.

Ceramic components tested in the ceramic engine test beds have accumulated 240 hours of operation. Although significant accomplishments have been achieved in the program, the ceramic components need much more development before they could be utilized in production gas turbines.

Where are we going in the future? DOE through the Oak Ridge National Lab and NASA have initiated generic ceramics programs, also called Ceramic Technology Project. This program is organized to ensure that complimentary efforts of universities, industry and the Government provide new, tougher, more reliable and easier to produce ceramics or derivatives.

As previously discussed, the AGT 101 program provided significant accomplishments in the development of first generation ceramics. However, the ceramics need considerably more development before they can be used commercially.

We know that questions relating to second generation materials, reliability, supply, infrastructure and demands of high quality components produced in cost effective quantities remain unanswered. The value of using realistic operating hardware when attempting to answer these questions is beyond doubt.

The AGT and the ATTAP programs provide already paid for test rigs and engine test beds for developing and evaluating the next generation of ceramics, once the parts are fabricated.

DOE has planned the ATTAP program to continue the ceramic technology effort that was initiated in the AGT and the Ceramic Technology Project programs, such that the United States will not lag behind world competition. The ATTAP will be initiated in July of 1987 and will be a five year program and will culminate in the successful durability testing of improved ceramics in the engine test beds.

We will concentrate on ceramics in this program, the auto companies will not be involved at this point in the ATTAP program.

What if we don't go forward? Ceramics development in this country will slow dramatically. Since the technology is still considered long range and high risk, U.S. industry will devote limited resources to bring ceramics to production status.

Foreign competition will bypass U.S. industry and offer ceramics for many applications before our industry does. Ceramics development is a national goal in Japan. Universities, industry and the Government seem to have a well organized effort.

The world oil supply is limited, as we heard earlier, even without a return of the fuel crisis, U.S. industry will be ill prepared without alternative fuel efficient and multi-fuel burning powerplants.

What do we recommend? We recommend that we continue the DOE and NASA ceramic technology projects. We recommend that the ATTAP program be continued into FY 1988, to evaluate the next generation of ceramics. We recommend that both AGT contractors are retained for the ATTAP program.

Mr. McCURDY. Why is that important? You heard the witness, Msis Fitzpatrick, before you say their intention was for it to be one. Why do you think it ought to be two?

Mr. STRAIN. We have built up seven years of experience at each team. Each team uses different approaches to the engine, different challenges are exhibited in the two types of engines that are being used. I feel that in this country, the amount of effort devoted to ceramics technology development should be increased and certainly not decreased and we should not disband one of these teams.

Mr. HELMS. May I add to that, please?

Mr. McCURDY. Certainly.

Mr. HELMS. As one does research and development, which is what we are participating in, it is absolutely, absolutely essential to iterate on the disciplines that may be involved, as we attempt to apply ceramics to heat engines. There are many disciplines involved; materials; mechanical designs; non-destructive evaluations and so forth.

We have found that by and large, the work that has been done at Garrett and at General Motors has been complimentary. Very seldom is there duplication. We have used different approaches to metals. For example, I showed a chart on candidate materials. We have agreed in essence that we will not duplicate each other's efforts but will be in hot pursuit of a variety of chemistries so that we can find the right ones and then we will share between us those kind of materials. Now, that's not collusion. That's good sense in R&D.

Mr. McCURDY. Well said. Thank you.

Mr. STRAIN. We recommend that $6 million be provided to each contractor for FY 1988 and that the estimated total ATTAP funding be about $30 million per each contractor, and that's over the five year period that we are talking about. This does not include the cost for NASA project management.

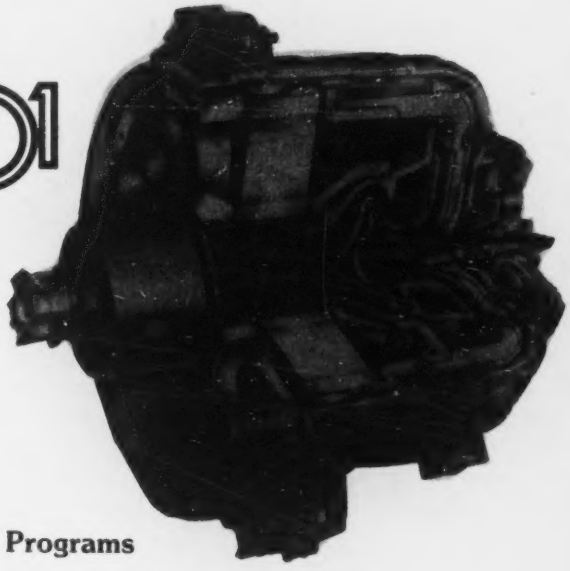
Finally, we maintain that the U.S. ceramics technology momentum must be continued.

[The prepared statement of Mr. Strain follows:]

Testimony
Before The
Committee on Science and Technology
Subcommittee on Transportation,
Aviation and Materials
United States House of Representatives

PROGRESS REPORT
GARRETT
ADVANCED GAS TURBINE PROJECT

AGT101



3 MARCH 1987

EDWIN STRAIN
Manager, Government Programs
Power Systems
Garrett Turbine Engine Company

Allied Signal Technologies

GARRETT

0507

GARRETT TURBINE ENGINE COMPANY
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

E. E. STRAIN

Manager, Government Programs,
Power Systems

Education

B.S., Aeronautical Engineering, Northrop Institute of Technology, 1962

Graduate Study, Aeronautical Engineering, UCLA

Work History

1968 to date: Garrett Turbine Engine Company

- Manager, Government Programs
- Manager, Military Programs
- Program Manager
- Program Administration

1965 to 1968: Rocketdyne

- Project Development Manager

1964 to 1965: Aerojet

- Manager of Small Engines Advanced Technology

1957 to 1964: Rocketdyne

- Project Engineer
- Field Engineering Manager
- Development Engineer

Responsibility/Experience

Mr. Strain has served as manager of numerous open- and closed-cycle gas turbine programs at GTEC. A majority of the programs were Government sponsored. Some of the programs and sponsoring organizations are listed below:

- Gaseous Diffusion Compressors/Valves-DOE/Union Carbide/Goodyear
- Advanced Gas Turbine - DOE/NASA
- Brayton Isotope Power System - DOE
- Brayton Conversions Module - DOE/JPL/NASA
- Closed Cycle Gas Turbine Heater - DOE
- Advanced Cogeneration Systems - DOE/NASA
- AH-64A Auxiliary Power Unit - Hughes/U.S. Army
- Enhanced Oil Recovery Cogeneration System - GWF Power Systems
- Alternate Fuels Evaluation - U.S. Air Force
- Gaseous Diffusion Compressors - Bechtel Corp.
- Improved Gas Turbine - Ford Motor Co.
- Ceramic Technology Readiness - DOE
- DIVAD Primary Power Unit - Ford/U.S. Army
- B-1 Secondary Power - Rockwell/USAF
- F-18 APU - Northrop/U.S. Navy
- F-15 Secondary Power - McDonnell Douglas/USAF
- C-2 APU - Grumman/U.S. Navy
- S-3A APU - U.S. Navy
- Aviation Ground Power Unit - Development Sciences/U.S. Army
- Large Aircraft Start System - Libby Corp./USAF

Additional experience at GTEC has involved project administration tasks associated with open- and closed-cycle gas turbine programs.

At Rocketdyne and Aerojet, Mr. Strain performed a variety of engineering and management functions related to the development and production of rocket engines. Significant programs in which he was involved were the Gemini, Apollo, Atlas, Thor, and Saturn rocket engine and system development and production.

Professional Affiliations

- American Helicopter Society
- AIAA

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GARRETT TURBINE ENGINE COMPANY
A DIVISION OF THE GARRETT CORPORATION
PHOENIX, ARIZONA

Mr. Chairman and Members of the Committee:

My name is Edwin Strain. I am Manager of Government Programs, Power Systems at the Garrett Turbine Engine Company, a Division of The Garrett Corporation (an Allied-Signal Company) (Figure 1).

Garrett has been working on the Advanced Gas Turbine (AGT101) Program under contract to the Department of Energy and NASA since October 1979. Garrett is the prime contractor. Major subcontractors supporting us in this program have been Ford, SOHIO, Corning Glass Company, and AiResearch Casting Company (another division of Garrett).

The AGT101 team has been developing high-risk, long-range technology for advanced automotive gas turbines for future automotive and other power plant uses. Major emphasis of the program has been to develop ceramic component technology for gas turbine engines.

In this testimony, we wish to focus on why this country needs the ceramics technology that has been provided only by the AGT program (Figure 2) and why ceramics need continued U.S. Government support under the Advanced Turbine Technology Applications Project (ATTAP).

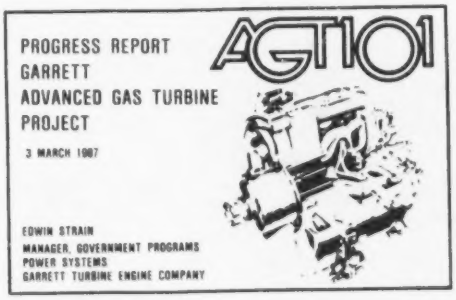

Figure 1. Testimony Before the Committee.

U.S. NEEDS CERAMICS TECHNOLOGY
THAT HAS BEEN PROVIDED BY THE
AGT PROGRAM AND REQUIRES CONTINUATION
UNDER THE ATTAP PROGRAM

Figure 2. Today's Focus.

I. WHAT IS CERAMICS?

- o Ceramics is a science related to nonmetallic and inorganic materials.
- o Silicon, nitrogen, and carbon are elemental constituents (i.e., sand).

II. WHY IS CERAMICS IMPORTANT?

- o Elemental constituents are readily available in the U.S. in an inexhaustible supply.
- o The need for strategic materials[1] is reduced (many heat engines, including gas turbines, employ strategic materials).
  - Reduced reliance on foreign sources[2], improving position of National Security.
  - There are not enough strategic materials in the world for automotive gas turbine production.

[1]"A strategic material is one for which the quantity required for essential civilian military uses exceeds the reasonably secure domestic and foreign supplies, and for which acceptable substitutes are not available within a reasonable period of time." Office of Technology Assessment, Strategic Materials: Technology to Reduce U.S. Import Vulnerability (January 1985), p. 13.

[2]"Three nations, South Africa, Zaire, and the U.S.S.R., account for over half of the world's production of chromium, cobalt, manganese, and platinum group metals." Ibid., p. 7.

- Cost of strategic materials for an automotive gas turbine is prohibitive.

o Ceramics[3] offers the automotive gas turbine:

- Capability to operate at higher temperatures without cooling, thus providing higher efficiency
- Better fuel economy
- Substantially lower cost potential
- Adequate raw material for mass production
- Lower friction (tribology)
- Lower weight
- Lower inertia of rotating parts (less energy) (Figure 3)

III. WHERE ARE WE IN CERAMICS TECHNOLOGY DEVELOPMENT?

o The AGT101 program has processed over 16,300 first-generation ceramic parts for evaluation.

- MATERIALS AVAILABLE IN U.S. IN INEXHAUSTIBLE SUPPLY
- NEED FOR STRATEGIC MATERIALS REDUCED
- CERAMICS FOR AUTOMOTIVE GAS TURBINE ARE ESSENTIAL
  - COST
  - HIGHER EFFICIENCY — BETTER FUEL CONSUMPTION
  - ADEQUATE RAW MATERIAL FOR MASS PRODUCTION

Figure 3. The Importance of Ceramics.

[3]"Ceramics, composites, and unconventional metallic materials have properties that suggest they might serve as substitutes for conventional materials that require strategic metals." Ibid., p. 52.

o Component and engine testing has been conducted under actual operating environment conditions.

o Ceramics is at the stage of development that metallurgy was 30 years ago (Figure 4).

IV. WHY HAS THE AGT PROGRAM BEEN IMPORTANT?

o The AGT program has been the major U.S. Government/industry-sponsored program devoted to moving the focus of ceramics from the research laboratories to a practical application -- an automotive gas turbine engine (Figure 5).

o The AGT program has been the only one in the U.S. that has allowed an all-ceramic engine hot section to be designed from inception (Figure 6).

o The program has allowed ceramics expertise from the auto, gas turbine, ceramics industries, and the government to develop ceramics technology and integrate this technology into the gas turbine operating environment via test rigs and engine test beds -- the only practical approach to ceramics technology development.

o The program has allowed the team to advance this long-range, high-risk technology, which no individual company could afford.

- AGT101 HAS PROCESSED OVER 16,300 FIRST GENERATION CERAMICS PARTS
- COMPONENT AND ENGINE TESTING UNDER ACTUAL OPERATING ENVIRONMENT
- CERAMICS ARE 30 YEARS BEHIND METALS DEVELOPMENT

Figure 4. Ceramics Technology Development Status.

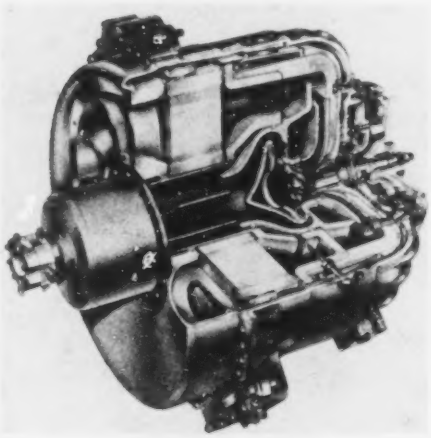

Figure 5. AGT101 Power Section.

- The program has provided the time and resources required for an iterative give-and-take ceramics design and development effort.
- The program has allowed the fabrication of test rigs and engine test beds for extensive ceramics development and evaluation.
- Without the AGT program, ceramics development would take much longer and cost much more.
- The program has allowed the U.S. industry to stay competitive with foreign ceramics technology development of high technology materials (Figure 7).

V. ARE OTHER GOVERNMENT AGENCIES AND INDUSTRY INTERESTED?

- All the military services have expressed interest in ceramic gas turbines. The AGT program has served as the focus for U.S.

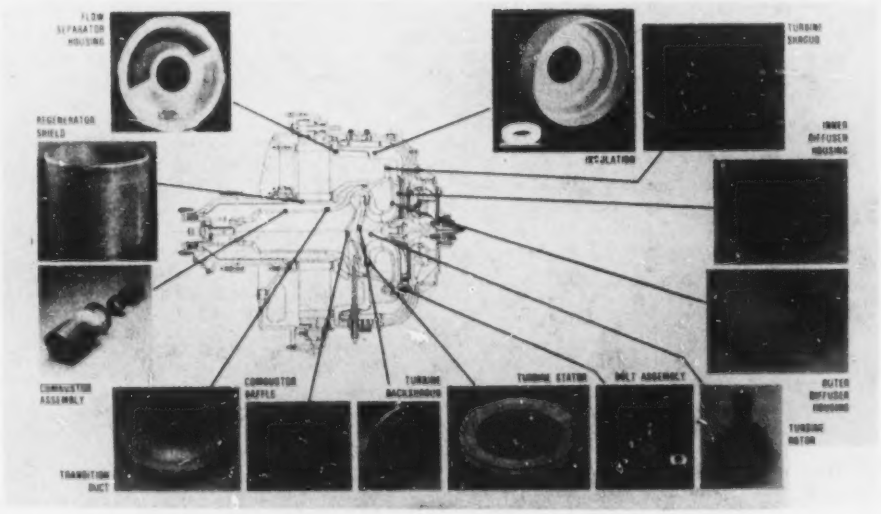

Figure 6. AGT101 Ceramic Components.

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- FOCUS OF CERAMICS TECHNOLOGY DEVELOPMENT IN U.S.
- CERAMICS BEING DEVELOPED BY INDUSTRY AND GOVERNMENT EXPERTISE IN THE MOST EXPEDITIOUS AND PRACTICAL WAY
- CERAMICS TESTED AND EVALUATED IN ACTUAL OPERATING ENVIRONMENT
- ONLY PROGRAM THAT HAS ALLOWED DESIGN OF CERAMIC GAS TURBINE FROM INCEPTION
- HAS ALLOWED U.S. INDUSTRY TO STAY COMPETITIVE WITH FOREIGN CERAMICS TECHNOLOGY DEVELOPMENT

Figure 7. The Importance of the AGT Program.

Government interest in ceramics. The services wish to take advantage of the work sponsored by the AGT and ATTAP programs. This work should continue.

- o The aircraft industry is interested in gas turbines that are more efficient, lighter weight, and less expensive. The use of ceramics offers these potential gains.
- o The AGT101 is a candidate for a solar generator set currently being considered for long-range development by the DOE.
- o A ceramic AGT101 derivative has been studied by NASA for aircraft propulsion application.
- o Industrial gas turbines are candidates for ceramics. Gas Research Institute is sponsoring development of a 50 kW advanced cogeneration system. The second generation system will employ ceramics.
- o U.S. industry is evaluating ceramic turbocharger turbine wheels for automotive application.
- o Ceramic components are beginning to be employed by industry for a wide range of production applications (Figure 8).

- AGT PROGRAM HAS SERVED AS FOCUS FOR GOVERNMENT INTEREST IN CERAMICS
- OTHER APPLICATIONS
  - CERAMIC GAS TURBINES FOR AIRCRAFT, SOLAR GENERATOR SETS, INDUSTRIAL ENGINES
  - TURBOCHARGER TURBINE WHEELS
  - WIDE RANGE OF CERAMIC PRODUCTS BEING INTRODUCED INTO PRODUCTION

Figure 8. Interest of Government Agencies and Industry Has Been Served by AGT Program.

VI AGT101 MAJOR ACCOMPLISHMENTS

- o The AGT101 Program is to be completed by June 30, 1987 (Figure 9). The program has successfully demonstrated the feasibility of applying ceramics to gas turbines.
- o Development of critical components, such as the high performance compressor and turbine, high temperature foil bearing and regenerator system was necessary to provide a valid engine test bed with which to evaluate the ceramic components development status.
- o Multifuel capability has been demonstrated in ceramic combustor rig tests.
- o The ceramic structural design approach has been validated with successful proof test of 137 components at 25 percent higher stress conditions than is expected in engine operation.
- o Structural ceramic components have accumulated over 40 hours of exposure to 2500F.
- o Ceramic turbine was successfully tested to full speed (100,000 rpm) in an engine.
- o All-ceramic engine successfully tested at 2200F for 85 continuous operating hours.

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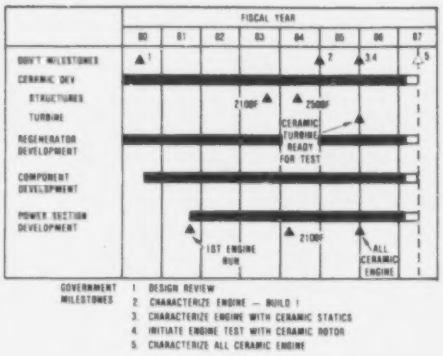

Figure 9. AGT101 Program Schedule.

- CERAMIC STRUCTURAL DESIGN APPROACH VALIDATED WITH PROOF TEST OF 137 COMPONENTS
- STRUCTURAL CERAMIC COMPONENTS ACCUMULATED OVER 40 HOURS TO 2500F
- CERAMIC TURBINE ENGINE TESTED TO FULL SPEED (100,000 RPM)
- ALL CERAMIC ENGINE TESTED TO 2200F FOR 85 CONTINUOUS HOURS
- CERAMIC COMPONENTS TESTED IN CERAMIC ENGINE TEST BEDS ACCUMULATED 240 HOURS OF OPERATION
- PROGRAM DEMONSTRATED FEASIBILITY OF APPLYING CERAMICS TO GAS TURBINES

Figure 10. AGT101 Major Program Accomplishments.

- DOE-ORNL-NASA INITIATED CERAMIC TECHNOLOGY FOR ADVANCED HEAT ENGINE PROGRAM IN 1984
  - ALSO CALLED CERAMIC TECHNOLOGY PROJECT
- DEVELOPING TECHNOLOGY BASE IN STRUCTURAL CERAMICS, CERAMIC COMPOSITES AND COATINGS CAPABLE OF PROVIDING RELIABLE AND COST EFFECTIVE COMPONENTS

Figure 11. DOE-ORNL-NASA Sponsoring Technology Research for Next Generation Ceramics.

- Ceramic components tested in ceramic engine test beds accumulated 240 hours of operation.

- Although significant accomplishments were achieved during the program, the ceramic components need much more development before they could be utilized in production gas turbines (Figure 10).

VII. WHERE DO WE GO IN THE FUTURE?

- DOE-ORNL and NASA have initiated generic ceramics programs (Ceramic Technology for Advanced Heat Engines Program). This program is organized to assure that complimentary efforts of universities, industry, and the Government provide new, tougher, more reliable, and easier-to-produce ceramics or derivatives (Figure 11).

- As previously discussed, the AGT101 program provided significant accomplishments in the development of first-generation ceramics, however, the ceramics need considerably more development before they can be used commercially. We know that questions relating to second-generation materials, reliability, supply infrastructure, the demands for high quality components produced in cost effective quantities, and others remain unanswered.

- The value of using realistic operating hardware when attempting to answer these questions is beyond doubt. The AGT and ATTAP programs provide already-paid-for test rigs and engine tests beds for developing and evaluating the next generation of ceramics, once the parts are fabricated.

- DOE has planned the ATTAP program to continue the ceramic technology effort ini-

tiated in the AGT and Ceramic Technology Project programs such that the United States will not lag behind world competition. The objective of the ATTAP is to continue to advance U.S. ceramics technology through the development of processes to fabricate and test components from the improved (next generation) ceramic materials, refine and enlarge ceramic properties experimental data base, expand analytical tools needed to support the ceramic industry, evaluate the reliability and durability of the next generation of high temperature ceramics, (Figure 12).

- The ATTAP will be initiated in July 1987 and will be a 5-year program. Figure 13 shows the technology areas to be considered in the plan. The initial part of the program will involve assessment to determine which ceramic materials are best suited for evaluation in ATTAP. Process development will then be initiated on the selected improved materials to fabricate test components for the AGT test beds.

- DEVELOP PROCESSES TO FABRICATE TEST HARDWARE FROM IMPROVED CERAMIC MATERIALS
- EXPAND CERAMIC PROPERTIES EXPERIMENTAL DATA BASE
- EXPAND ANALYTICAL TOOLS NEEDED BY CERAMIC INDUSTRY
- EVALUATE RELIABILITY AND DURABILITY OF NEXT GENERATION CERAMICS

Figure 12. ATTAP to Continue U.S. Ceramics Technology Development.

- 5 YEAR PROGRAM BEGINNING IN FY87
- ASSESS NEXT GENERATION CERAMICS FROM NASA, ORNL, DOE AND INDUSTRY
- SELECTED CERAMICS TO BE FABRICATED INTO AGT COMPONENTS
- COMPONENTS TESTED IN EXISTING AGT TEST RIGS AND TEST ENGINES (ACTUAL OPERATING ENVIRONMENT)
- ACCELERATED AUTOMOTIVE DURABILITY TESTING

Figure 13. ATTAP Will Use AGT Test Beds to Develop Next Generation Ceramics.

- A more complete materials property data base will be generated to support the analytical design effort. The analytical design tools include thermal and stress analysis to calculate reliability under engine operating conditions. Verification test data is required to support this analysis. In addition, models are needed to define time-dependent failure modes such as creep and stress rupture. The development and adaption of uniform design practices is required to advance ceramic technology and assure reliability.

- The ATTAP will culminate in successful durability testing of the improved ceramics in the engine test beds.

VIII. WHAT IF WE DON'T GO FORWARD?

- Ceramics development in this country will slow dramatically. Since the technology is still considered long range and high risk, U.S. industry will devote limited resources to bring ceramics to production status.

- Foreign competition will bypass U.S. industry and offer ceramics for many applications before our industry does. Ceramics development is a national goal in Japan. Universities, industry, and the government seem to have a well-organized effort.

- The world oil supply is limited. Even without a return of the fuel crisis, U.S. industry will be ill-prepared without alternative fuel efficient and multi-fuel-burning power plants (Figure 14).

- U.S. CERAMICS DEVELOPMENT WILL SLOW
- FOREIGN COMPETITION WILL BYPASS U.S. CERAMICS TECHNOLOGY
- RETURN OF FUEL CRISIS WOULD FIND U.S. AUTO INDUSTRY WITHOUT ALTERNATIVE FUEL-EFFICIENT AND MULTI-FUEL BURNING POWER PLANTS

Figure 14. Lack of Future Development Would Prove Detrimental.

IX. WHAT DO WE RECOMMEND?

- o Continue funding DOE and NASA ceramic technology projects.
- o Continue the ATTAP program in FY88 to evaluate the next generation of ceramics.
- o Keep both AGT contractors involved.
  - Fund $6 million per contractor in FY88*
  - Estimated total ATTAP funding $30 million per contractor (5 years)*
- o Maintain U.S. ceramics technology momentum (Figure 15).

- CONTINUE DOE AND NASA CERAMIC TECHNOLOGY PROJECTS
- CONTINUE ATTAP PROGRAM IN FY88 TO EVALUATE NEXT GENERATION CERAMICS
  - KEEP BOTH AGT CONTRACTORS INVOLVED
  - FY87 FUNDING - $6 MILLION PER CONTRACTOR*
  - ESTIMATED FY87-91 FUNDING - $30 MILLION PER CONTRACTOR*
- MAINTAIN U.S. CERAMIC TECHNOLOGY MOMENTUM

*EXCLUDING COSTS FOR NASA PROJECT MANAGEMENT

Figure 15. Recommendations.

*Excluding cost for NASA project management.

Mr. McCURDY. Thank you. Dr. Powers? Director of the Power Train and Systems Research Lab at Ford Motor Company.

Dr. POWERS. Thank you, Mr. Chairman.

We were asked to comment on electric vehicle programs, automotive gas turbines and also the advanced structural ceramics programs, so I will summarize our comments for the record.

Mr. McCURDY. Your full testimony will be submitted in the record.

Dr. POWERS. In 1985, Ford and General Electric completed a successful Phase I research program, called ETX-I, aimed at providing the technological foundation for a new concept in electric vehicle propulsion. This concept utilized an electronically commutated motor, integrated the motor and the transaxle, permitted a systems approach to power plant and braking control. It eliminated many of the disadvantages of previous electric vehicle designs and permitted the evaluation of an advanced battery, the sodium sulfur battery.

The second phase called ETX-II, is designed to eliminate some remaining uncertainties that prevent consideration of commercialization of the new concepts. This program was planned as a four year program and for the past two years, Congress has provided funding for it.

Ford believes that the ETX program represents an important opportunity for the United States to establish leadership in this field. The importance that we place on this work is demonstrated by the fact that although there are still significant developments required for success, Ford put its own funds at risk to continue the program when Federal funding sources did not materialize as planned.

In reviewing the proposed fiscal year 1988 budget, we note that no funds have been allocated to continue the ETX-II program, which was scheduled to be funded in the amount of $3.5 million in 1988 and half a million dollars in 1989.

We believe that if this omission is not corrected, it will deprive the United States of an opportunity to develop an important alternative to conventional petroleum based transportation.

Turning now to the advanced gas turbine programs, Ford has been developing turbine technology since the early 1950's. During the 1960's, the technology was dependent upon high temperature metals and Ford was one of the first to recognize the use of ceramics in gas turbines. During the 1970's, we performed a considerable amount of work on the development of ceramics technology and its application to turbine engines. In 1979, Ford joined with Garrett in successfully obtaining DOE funding for the development of a ceramics based advanced gas turbine technology.

While advanced gas turbine engines were viewed at that time as one of the more attractive alternative vehicle engines, Ford's primary interest was in ceramics technology for power plants of all types. We participated for seven years in this project.

Last year, Ford advised DOE and Garrett that we believe the ongoing DOE project would be best served by Ford transferring to Garrett its ceramic regenerator technology. The hardware is being updated to include the present state of technology developed in the AGT 101 program. This effort is expected to be completed by mid-year 1987 and will end Ford's participation in the turbine program.

Finally, with regard to ceramics materials research, we are performing basic structural materials research and application specific research, such as ceramics in all types of engines with major emphasis on diesel engines.

Our internal R&D programs in this field are necessarily small because of its very long term, high risk nature. Thus, Federal support of such programs is recommended.

In addition to our internally funded programs, we are participating in the major national program on advanced structural ceramics, which is underway at the Oak Ridge National Laboratory. Last year, we acquired an interest in Ceradyne, Inc., a small West Coast ceramics company. We are currently working with Ceradyne in the first of several joint development projects aimed at developing structural ceramics for automotive applications.

Our technical motive in these projects is to move ceramics technology from the laboratory to the manufacturing stage in order to address such issues as cost and reproducibility.

In conclusion, we welcome the chance to have been here today and give our comments. We are pleased with the congressional and Administration initiatives aimed at further support for R&D as one of the key aspects of improving this nation's competitiveness.

Thank you, Mr. Chairman.

[The prepared statement of Dr. Powers follows:]

HOUSE SUBCOMMITTEE ON TRANSPORTATION, AVIATION AND MATERIALS

Statement of Dr. W. F. Powers
Director, Powertrain and Systems
Research Staff
Ford Motor Company
March 3, 1987

Mr. Chairman and members of the Subcommittee, my name is Bill Powers. At Ford I am responsible for Powertrain and Systems Research. We are pleased to comment on Ford's role in the DOE programs that are the subject of today's hearing.

First, with respect to electric vehicles, Ford believes that the ETX program represents an important opportunity for the United States to establish technological leadership in this field. The importance that we place on this work is demonstrated by the fact that although there are still significant developments required for success, Ford put its own funds at risk to continue the program when planned funding sources for the program did not materialize and efforts to provide funds were delayed by the normal budget process.

In 1985, Ford and General Electric completed a successful research program aimed at providing the technological foundation for a new concept in electric vehicle propulsion. This concept utilized an electronically commutated motor, integrated the motor and the transaxle, permitted a systems approach to powerplant and braking control that eliminated many of the disadvantages of previous electric vehicle designs, and permitted the evaluation of an advanced battery - the sodium-sulfur battery.

This first phase, designated as ETX-I, confirmed the potential advantages of the novel features of the concept. The second phase, designated as ETX-II, is designed to eliminate some remaining uncertainties that prevent immediate consideration of commercialization of the new concepts. Even though the experimental powerplant, installed in a modified Ford LN7 vehicle, met all of the program objectives, several open issues still remain. The second phase is designed to eliminate some of the remaining uncertainties. These include:

- The ability to scale up the powerplant to a size suitable for a commercial van (considered to be the most promising potential application for this type of propulsion).

- Integration of the many electronic subsystems to reduce cost and improve reliability and manufacturability, including size reduction and other improvements in the power inverter.

- Development and application of the internal permanent magnet AC motor (a feature that is very attractive because of recent developments in high performance magnetic materials).

- Further testing to demonstrate the expected capability of the sodium-sulfur battery.

The ETX-II program was planned as a four-year program with the objective of advancing electric vehicle technology to the point where it would be possible to make informed decisions as to the potential commercial viability of vehicles incorporating the ETX technology.

For the past two years Congress has provided funding for the ETX-II program. Work during this time period has progressed at a good pace at both Ford and General Electric. GE's effort involves work on the motor, inverter, and controls as a major subcontractor to Ford.

If funding is not provided for the third and fourth years of the program, the efforts expended to date may be wasted. At this stage the risks are too high for Ford to assume the funding needed for the required research. Additionally, the research results are equally important to all potential electric vehicle manufacturers. Without the information expected from the completion of the ETX-II program, there is insufficient information to allow manufacturers to make a prudent decision concerning commercialization of this promising technology.

In reviewing the proposed FY 1988 budget, we note that no funds have been allocated to continue the ETX-II electric vehicle research program, which was scheduled to be funded in the amount of $3.5 million for FY '88 and $0.5 million for FY '89. We believe if this omission is not corrected, it will deprive the United States of an opportunity to develop an important alternative to conventional, petroleum-based transportation.

With respect to the advanced turbine program, Ford has been involved in developing turbine technology since the early 1950's. During the 1960's, the technology was dependent on high-temperature metals, and Ford was one of the first to see the possibility of ceramic materials for powerplants. During the 1970's we performed a considerable amount of work on the development of ceramic technology and its application to turbine engines.

In 1979, Ford joined with Garrett in successfully obtaining DOE funding for the development of ceramic-based advanced gas turbine technology. While advanced gas turbine engines were viewed at that time as one of the more attractive alternative vehicle engines, Ford's primary interest was in ceramic technology for powerplants of all types. We participated for seven years in this project.

Last year, Ford advised DOE and Garrett that we believed the ongoing DOE project would be best served by Ford transferring to Garrett its ceramic regenerator technology. The ceramic regenerator hardware is being updated to include the present state of technology developed in the AGT 101 program. This effort is expected to be completed by mid-year 1987 and will end Ford's participation in the turbine program.

Although Ford continues to be interested in gas turbine technology, we believe the most promising alternate vehicle engine by the year 2000 is the adiabatic diesel. Consequently our present emphasis is being directed to an internally funded ceramic adiabatic diesel research program. The ceramic adiabatic diesel engine has the potential to eliminate the cooling system, simplify the engine design, reduce engine weight, noise, emissions and friction, tolerate lower quality fuels and provide significant improvements in fuel economy. We have successfully tested a single cylinder structural ceramic adiabatic diesel for over 100 hours. Results from this test have confirmed our projections of reduced friction and improved fuel economy.

The adiabatic diesel is an example of an application-specific program. Ford is also involved in general ceramic materials research. In addition to internally funded research programs, we are participating in the major national program on Advanced Structural Ceramics, which is underway at the Oak Ridge National Laboratory, and last year we acquired an interest in Ceradyne Inc., a small west-coast ceramics company. We are currently working with Ceradyne in the first of several joint development projects aimed at developing structural ceramics for automotive applications. Our technical motive in these projects is to move ceramics technology from the research laboratory to the manufacturing stage in order to address such issues as cost and reproducibility. The broader objective is to develop a manufacturing base through the exploitation of near-term applications of all types, i.e., automotive and non-automotive.

With respect to the automotive industry, high volume mass production use of ceramics in the automobile has, to date, been limited to:

- Spark plug insulators (these are made of aluminum oxide by isostatic pressing, green machining and sintering).
- Catalyst substrates (these are made of cordierite by extrusion into a honeycomb shape and sintering).
- IC packaging ceramics (these are primarily aluminum oxide and are made in sheet form using a "doctor blade" process and sintering. The trend in the computer industry is toward more advanced multi-layer packaging. In the case of high power transistors, beryllium oxide is often used because it has high electrical resistivity yet high thermal conductivity).
- Oxygen sensors (these utilize yttria doped zirconia and sense the partial pressure of oxygen in the automotive exhaust gas).

An emerging area of advanced materials is the field of structural ceramics. Research and development in this area is going on worldwide and is particularly active in Japan. Structural ceramics include such families of materials as silicon nitride, silicon carbide, aluminum titanate, partially stabilized zirconia and zirconia-toughened alumina; many of these are multi-phase materials and included would be composites of these materials using fibers, whiskers and/or particulate toughening mechanisms. It is important to note that much of the work in Japan is government funded.

Low volume use of structural ceramics has begun in the Japanese automotive industry for silicon nitride turbochargers, tappets, glow plugs (diesel) and pre-combustion chambers (diesel), and, in Europe, for aluminum titanate exhaust port liners. The use of structural ceramics in the adiabatic diesel promises significant improvements which are being evaluated in our own research programs.

At this point, structural ceramics show considerable promise but need further development in the areas of reliability and reproducibility. The following are suggested as areas of needs/opportunities:

- A better understanding of ceramic process science is required as the basis for manufacturing reproducible, consistent materials in complex shapes to near-net-shape.

- A better understanding of starting powder purity and grain boundary control is needed, especially as this relates to high temperature, time dependent strength,and thermal/electrical conductivity.

- Tougher ceramics such as ceramic composites are required to improve handling and reliability.

- Manufacturing development is required for inexpensive starting powders, and inexpensive forming and firing processes in relationship to the functional benefits realized through the use of ceramics.

- Design methodologies are needed to utilize ceramic materials in engineering applications. In particular, methods are needed to assure adequate lifetime reliability in any given design.

The opportunities for structural ceramics are significant. They include many high temperature/high wear applications such as lightweight valves and valve guides, low wearing cams and tappets, cutting tools and manufacturing fixtures. In the adiabatic diesel engines, ceramics are being evaluated for the cylinder, cylinder head and piston.

Realization of the full potential of structural ceramics in industry depends upon successful materials/process R&D so that high strength, reliable ceramics can be made in high volume and at a favorable cost/benefit ratio. Achievement of this realization is difficult and long-range. Ford has R&D programs in the field of structural ceramics, but such industrial research is necessarily small because of the very long-term nature of this work. National support of such programs is therefore recommended, not only to keep the United States industrially competitive, but also because structural ceramics have direct application to areas of national defense. Success would have direct impact on major engineering products, such as the internal combustion engine.

In summary, Ford welcomes the interest of the Subcommittee in automotive-related research and development. We are most pleased with the Congressional and Administration initiatives aimed at further support for research and development as one of the key aspects of improving this nation's competitiveness.

Mr. McCURDY. Thank you, Dr. Powers. Mr. Nightingale?

Mr. NIGHTINGALE. Thank you, Mr. Chairman. Accompanying me today is—for the sake of a twisted back and a kink neck, may I stand? I think my voice can carry in the room.

Mr. McCURDY. Sure.

Mr. NIGHTINGALE. I'd like to point out that accompanying me today is Mr. Greg Gutgsell from John Deere Company, and if I may, I would like to have Mr. Gutgsell make a minute or two comment on John Deere's role in the Stirling engine program. I have submitted written testimony which I ask to be placed in the record.

Mr. McCURDY. It will be. Thank you.

Mr. NIGHTINGALE. To summarize the written testimony, I'd like to touch upon the status of the automotive Stirling engine program, touch upon the activities that we perceive going on and comment on the industry and consumer interest in the Stirling engine, counter to the earlier remarks this afternoon, and finalize with recommendations for a proposed Stirling technology effort.

I think it is important to remember why we started the Stirling program back in 1978 and that was not only did it have the potential for high fuel efficiency but multi-fuel capability, it is very clean and very quiet. In fact, the Stirling engines that we installed in our cars, of course, have no catalytic converter and no muffler and you can literally put your hand almost on the exhaust because the temperature is so low.

The goals of the program were very, very specific when we began, to develop an automotive Stirling engine and that goal had with it very specific objectives, 30 percent better fuel economy, some very stringent emission goals, quiet and safe operation, and then to transfer the technology to the United States.

Back in 1978, most of the Stirling engine technology resided in Europe by the Phillips Company and in United Stirling in Sweden.

All of my comments today are going to be centered around the engine of the program today, and that is the Mod II. Here is a full scale mark-up of the Mod II exactly to scale. It generates approximately 80 horsepower and you can see that it is now down to the size where it is competitive with high speed spark ignition and diesel engines and can fit into the current hoods of automobiles.

The engine in the test cell at MTI is pictured here.

[Slide.]

Mr. NIGHTINGALE. We have one engine on test and I will be touching upon some of that in a moment.

To proceed with the status of the program and give you an up to date reading on it, we have in Mod II—we started testing approximately a year ago, it has accumulated over 400 test hours, generated 54 kilowatts and a peak efficiency of 38 percent. More importantly, its size has been decreased and its weight such that its specific weight is at 5.5 pounds per horsepower.

Just to give you a little more detail on that, here is a plot of the engine data. This is not projections. These are data from which we obtained off the engine in the cell. You can see our maximum power line here. You can see the engine runs from anywhere from 1,000 rpm up to 4,000 rpm and a minimum power line here. As you know, in the automotive application, you have to vary significantly

in speed and power as you meet the demands of the driver on the road.

The efficiency of the engine is proving to bear proof relative to our projections, these are data points, not projections. We have obtained a maximum efficiency here, approximately 38 percent. Because the engine, as any heat engine, varies and varies in pressure, it can get down to as low as about 25 percent peak efficiency.

Mr. MCCURDY. How does that compare—you have 38 percent. How does that compare with other engines, other types of engines, as far as shaft efficiency?

Mr. NIGHTINGALE. I won't profess to be a diesel expert or IC expert but I would say that the competition is approximately in the 33-34 percent range. This is on unleaded gasoline as well.

Mr. MCCURDY. Thank you.

Mr. NIGHTINGALE. I want to point out the progress made in the program. I think this is a significant figure here. I will spend a couple of seconds on it.

Back in 1978, when we started with the technology, as was earlier referred to, the specific weight of the engine at that time was close to 14 pounds per horsepower. The fuel economy was very, very low, compared to high speed I.C. It was well below high speed I.C. and in fact in the absolute value, about 18 miles per gallon.

Of course, the acceleration was totally unacceptable. One of the measuring sticks for performance of the vehicle was acceleration time from 0 to 60 miles per hour, and that's reflected here, and you can see we were way high, in the high 30's relative to that parameter.

Over the years, we were able to improve upon the technology such that we have a vehicle now that performs and its acceleration is 16 seconds, and Mod II will be down around 12. The mileage now is 15 percent above a comparable IC. In other words, we are approximately halfway in terms of our fuel economy goal and the Mod II, of course, will be much, much higher.

This is the number I mentioned before, 5.5 pounds per horsepower. So, we have a very competitive power plant. I wouldn't deceive you and say the job is finished. It isn't. We have brought the technology a long way.

Shifting now to another aspect of the program, I have to refer to the schedule and the timing that we are on. Earlier last year, approximately a year ago, I'm sure you are aware that there were some deferral actions. The money was stopped in terms of its flow to the program for several months. It caused not only delays in the program, but we actually had to conduct some layoffs, unfortunately, such that we are now projecting that the program, still on the fiscal year 1987 funds, will be finished in the middle of 1988.

So we're not here looking for 1988 funds to finish the ASE program. We will live up to our commitments and our promise in testimony that we would complete the program on the fiscal year 1987 appropriated funds.

So the program is such that we are currently—here we are at this point in time—we are currently testing the No. 1 engine, the data which I showed you. We have a second engine coming on board and later a third engine, and we will be putting the Mod 2

into a General Motors Celebrity later this year, and then approximately in April 1988 we will demonstrate the program goals.

Another very, very important aspect to any new engine technology is its life and reliability. In fact, if you would talk to folks from industry, they might say that it is, in fact, almost the only criterion, due to warranty costs and so forth. So we continue to pursue that aspect of the engine technology.

And on this next Vu-graph is shown a bar graph of the number of hours we have achieved each year on our engines, first on the Mod 1, which was an earlier generation, and now you can see where our hours on the Mod 2 are coming in. Not much in life and reliability yet, and I think I have to emphasize that point.

We are quite encouraged, though, at the rate that the Mod 2 is coming on board, because here is plot—I'm sorry for the colors there; the red line does not show up very well—but we have obtained approximately 200 hours on that engine over the last 60 days. So it is now starting to really bear fruit in terms of reliability.

The second goal of the program, as I pointed out, and a very difficult one for us, being a research and development house, was the transfer of the Stirling technology to American industries. Certainly, if Stirling engines were to be a viable product here in the United States, it wasn't going to happen because of MTI's manufacturing capability. It had to be transferred to industry manufacturers.

And that is why John Deere is on the program. They are a subcontract within the program and cost-sharing some of their efforts. They are in the process of taking the design of the Mod 2 and reviewing it to reduce the manufacturing cost, and we have actually started the transfer to the John Deere folks in terms of Stirling technology. They understand some of the particular components associated with the Stirling engine.

To summarize the effort on our part to transfer the technology to end-users, consumers, and manufacturers within the United States, I would like to spend a few seconds on this Vu-graph.

At the core, of course, is the Mod 2 engine with John Deere focused as the engine manufacturer. There have been two major thrusts in terms of markets, one to the vehicle application, because that's what it was designed for; also, a major thrust is stationary applications, because it has advantages, as were recited earlier.

One particular successful effort was an Air Force van program with the Air Force, using NASA technology utilization funds. In other words, the funding for this effort came from separate sources, and, in fact, that's what all of this is about, us trying to get funding from other sources for end-users to evaluate the technology and move on into a commercial venture with the core technology and the manufacturer as the focal point.

And that's the process, and that's the status of where we are today. We are dealing with the Postal Department—I'm sorry—the Postal Department is over here. They have come to us as a result of their impressions from the Air Force van program. They have asked us if we could manufacture 50 Mod 2s and a fleet demonstration for postal vehicles. We are currently in the planning phase of that effort.

In the stationary area, we have talked to several gas industries in the use of this engine for co-gens and heat pump applications, as well as the Gas Research Institute.

And lastly, we have already submitted a proposal to the Army, and the Army has seen the Mod 2 and are interested in it for silent power.

Focused around the van program—I'll just spend a couple of seconds—the emphasis on the Air Force van program is not so much the military aspects, although there is an interest there, but it is the fact that we have industry involved in the program, not only John Deere, but the American Trucking Association and Purolater. And they are the ones who are watching and monitoring the progress within that program for possible commercial applications.

Here is a picture of the Air Force van. That van is on Langley Air Force Base. It's been turned over to a third party. They use it on the operational line. I believe that's Mr. Gutgsell in the driver's seat there. And so far to date it has over 400 hours. It's used 16 hours a day sometimes, and we are just learning a great deal on reliability and durability relative to the engine, as well as the performance of it. So far, it's been very successful.

We did also have a generator set which was taken down to one of the Army bases and run for possible use of diesel fuel and, of course, to evaluate its silent operation. And as I said earlier, we are currently working with the Army to try to define that program.

If I could just move on with one Vu-graph now of our findings in Japan, we visited Japan last April, and the purpose of that visit was to evaluate the level of their technology in Stirling engines. We knew that they were working on Stirling engines.

To summarize, fundamentally what they call a "Moonlight Project," funded by the Japanese Government, and it's approximately $40 million. It's a six-year program. On that program, they are developing three—two levels of Stirling engines, 3-kilowatt engines and 30-kilowatt engines, and the participants—Aisin Seiki, which is a company from the Toyota Motor Division—and when I was at Aisin Seiki, they showed us their 30-kilowatt engines, which they are developing for heat pumps running on natural gas, but I also discovered that they were putting another engine, which they are developing under their own funds, into special vehicles, as we are with vans. And they run it on a track, and it's a Toyota truck.

That's all the information I have, except that they started the development in 1975, and they picked up when they heard that we were starting to develop an automotive Stirling engine.

The Mitsubishi folks are also very, very big and have 20 people dedicated to a heat pump, 3-kilowatt Stirling engine for the heat pump application, and, of course, Mitsubishi is quite a competitor in that area.

The other two companies are not all that active. They are part of the program. But we would say that Aisin Seiki and Mitsubishi are the ones who have a commercial track. Aisin Seiki clearly says that they are attempting to commercialize the product by 1990.

If I could just summarize, then, Mr. Chairman, I think that by virtue of the ASE program, the foresight of Congress in appropriating the money to the program over the years, that we have a lead-

ership in Stirling technology in the United States, a professional nucleus at MTI. We have initiated non-government monetary support for these various applications, and we have increased interest in non-automotive applications.

There is no question that there is a foreign competition that exists now, and that it is a race to see if we will have ours either in one of our markets or another.

I should like to add, before I get to my last two Vu-graphs, which are my recommendations, that we just finished a discussion with Ford. They have, as a result of the data coming off the engine, requested all of the information on the engine, and they are going to go through an internal two-month study to look to the use of the engine in trucks.

When I asked them why they were interested, they said, in the case of trucks, the silent operation and the multi-fuel potential of the engine was what was attracting them to that application.

So I wish I could give you more positive readings, but at least we have once, for the first time in eight years, an automotive company that is expressing positive interest.

So I think to close with my recommendation, I think that what is necessary is to continue the development of the Stirling technology under the support effort, and that that be initiated in FY '88 as a follow-on to the ASE program. And the goals would be to continue to advance the technologies, to remain ahead of the foreign competition, and that that authorization for 1988 should be approximately $8 million.

To be a little bit specific—and this is my last Vu-graph—when I say "advance the technologies," I mean that the purpose of that work would be to include efficiency and operational performance of the unit, certainly develop life and reliability—200 hours or 400 hours is not acceptable—and continue to reduce the manufacturing cost. The technology would be in the heat input systems, both in combustors and heat exchange components, seal systems—and that was touched upon earlier today in earlier testimony—the drive system and materials and control system.

And I think, touching upon materials, in the Stirling engine there is no sizeable technology leap that has to be made to make the engine a commercial venture. What is necessary is simply to reduce its manufacturing cost and make it competitive to penetrate these markets.

That concludes my presentation, Mr. Chairman, and if I could I would like to turn to Mr. Gutgsell for a couple of minutes of discussion on John Deere's participation in the program.

[The prepared statement of Mr. Nightingale follows:]

HEARINGS ON DOE TRANSPORTATION PROGRAMS

Subcommittee on Transportation, Aviation, and Materials
Committee on Science, Space, and Technology
U.S. House of Representatives

Stirling Engine Program

Presented by:
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Assistant General Manager
Stirling Engine Systems Division

March 3, 1987

About the Author . . .

Noel P. Nightingale

Mr. Noel Nightingale is the Assistant General Manager of the Stirling Engine Systems Division of Mechanical Technology Incorporated, Latham, New York, a high-technology research, development, and manufacturing company. He managed the Stirling engine program almost since its inception in 1978 and has authored various papers on its progress. He has also been instrumental in transferring Stirling technology to industry and product users during the past few years. Prior to that, he was employed for more than 12 years with Pratt and Whitney Aircraft, a division of United Technologies Corporation. During that period, he undertook technical and managerial roles in the design, analysis, and development of military and commercial gas turbines and large (100 MW) ground power units. He also has management experience in multinational consortiums and aircraft maintenance. Mr. Nightingale holds a Bachelor Degree in Mechanical Engineering from the University of Toronto and Master Degrees in Engineering Science and Business Administration from Rensselaer Polytechnic Institute.

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TESTIMONY ON THE STIRLING ENGINE PROGRAM
before
Subcommittee on Transportation, Aviation, and Materials
Committee on Science, Space, and Technology
U.S. House of Representatives

Mr. Chairman, members of the subcommittee, my name is Noel Nightingale, and I am the Assistant General Manager of the Stirling Engine Systems Division (SESD) of Mechanical Technology Incorporated (MTI). The Automotive Stirling Engine (ASE) Development Program is funded and managed by the Department of Energy (DOE). The NASA-Lewis Research Center located in Cleveland, Ohio, is responsible for the project management of the program. MTI is the prime contractor on the program. MTI is a high-technology research, development, and manufacturing company located primarily in the state of New York, with wholly owned subsidiaries in Michigan and California. The SESD engages approximately 100 people in the development of Stirling engines for a variety of applications. This team, primarily professionals, was formed by MTI in response to the national need for an advanced energy-efficient technology, in this case, the Stirling engine.

Mr. Chairman, MTI appreciates the opportunity to appear before this subcommittee to testify on the ASE development program. It is my pleasure to report that the ASE program continues to achieve its technical goals, while remaining within budget. The program is on target for the development of a Mod II engine and the final demonstration of the overall program goals.

My testimony recalls the history of the ASE program and reports on its current status. I shall also comment on Stirling engine development activities in Japan and the threat they pose to U.S. industry. Further, I shall comment on the increased interest in the Stirling engine being demonstrated by industry and potential consumers. Although significant interest in Stirling technology is being shown by industry, the path to commercialization is long. While commercialization is in process, Stirling technology must continue to advance and improve in order for the United States to maintain the technical edge over foreign competition made possible by the successful ASE program. To this end, I shall close with a request for a FY88 authorization of $8 million for a Stirling Technology Support effort. This funding would ensure that the United States maintains the lead in this valuable technology while efforts to commercialize the engine continue with separate funds from industry participants. All figures referenced in the text are included, for your convenience, in numerical order at the end of this testimony.

BENEFITS OF THE STIRLING ENGINE

To achieve national acceptance, a Stirling engine developed for the automotive application must meet a number of stringent requirements. It must be small enough to fit within the structure of current vehicles, which are becoming more and more streamlined each year. It must provide sufficient power to meet the demanding performance requirement of today's cars. It must be efficient over a wide range of power and speed by providing high fuel economy both in the stop-and-go environment of city driving and the constant-speed cruising of highway driving. But, most importantly, it must be inexpensive to manufacture in order to provide manufacturers an economical advantage to penetrate

existing markets, as well as an incentive to develop new market sources. It must be inexpensive to operate in order to provide consumers an economical reason for choosing a new technology that does not dislocate their spending habits. Until the creation of the Mod II and the technology developed under the ASE program, Stirling engines were unable to meet these requirements. Now that the Mod II development is underway, and good data are forthcoming, industry and consumers are only now becoming aware that Stirling power is rapidly emerging as a viable option.

The wisdom of Congress in deciding to develop the Stirling engine for the automotive application continues to be confirmed. A high level of technology is required to develop any engine for the automotive application. Once the goals are achieved, however, there are almost immediate windfall benefits to other applications. Promising applications now include light-duty vehicles, generator sets, irrigation pumps, solar electric units, heat pumps, industrial prime movers, underwater and other marine applications, and farm equipment. Whereas the fallout of ASE technology to other applications may be a somewhat subjective assessment, it serves to underscore a key national benefit -- that the ASE program provides the United States with a core technology having a host of spin-off applications. These, in turn, can provide our nation with a greater capability for conserving energy, new products for improving the American standard of living, and new products for export, as well as maintaining the technological leadership in those areas.

The payoff of introducing Stirling technology into the United States holds a vast potential for new jobs related to new products, their manufacture and service, as well as an increase in associated trade employment. The multifuel capability of the Stirling engine will provide personal and national security in times of petroleum dislocation. The Stirling engine will meet the emission standards defined in the Clean Air Act, thereby contributing to the national effort to upgrade our environment. The ASE also provides an advantage to improving our noise environment, since the noise level emitted from a Stirling engine is much lower than that of conventional engines, such that a Stirling engine does not require a catalytic converter or a muffler. Finally, the overall potential for conserving valuable fuel resources through the use of more efficient Stirling engines in automobiles and in other applications is immense.

ASE PROGRAM HISTORY

In Section 302(b) of Public Law 95-238, the U.S. Congress charged the DOE with initiating programs leading to the development of advanced automotive propulsion systems. DOE selected two basic engine cycles: the gas turbine and the Stirling. The Stirling engine was selected because of its intrinsic capability to provide high cycle efficiency; i.e., when installed in an automobile, the Stirling engine can attain a higher fuel economy than that of conventional power systems. Further, since the engine uses a continuously burning external combustion system, it is capable of using a variety of liquid fuels while maintaining low emission and noise levels.

The logic set forth in the program was to develop two experimental engines in sequence. The first engine, the Mod I, was a new engine design based on Stirling engine technology as it existed at the beginning of the program in 1978. The second engine, the Mod II, was to incorporate technology advancements made

during the course of the ASE program. The Mod II was also to demonstrate the specific program objectives stemming from the public law, including

- A 30% improvement in fuel economy over a comparable production spark-ignition engine
- Operation within strict emissions standards ($NO_x \leq 0.4$, HC $\leq$ 0.41, CO $\leq$ 3.4 g/mi, and particulates $\leq$ 0.2 g/mi)
- Use of alternative fuels
- Reliability and life expectancy comparable to commercial engines
- Initial cost and life-cycle cost competitive with conventional engines
- Acceleration suitable for safety and consumer considerations
- Noise characteristics meeting federal standards.

Although the time frame and magnitude of the ASE program have been altered by budget restrictions over the past years, progress toward the goals and objectives has been consistent. MTI has done its utmost to meet the will of Congress by maintaining the schedule of the program. The $8 million authorized by this committee last year and supported by Congress will enable MTI to complete the ASE program. The program is currently entering its final phase, whereby the Mod II engine will demonstrate the program objectives.

ASE PROGRAM STATUS

The Mod II engine was designed to meet the program goal of providing a highly efficient automotive power plant with a competitive manufacturing cost (see Figure 1). During the past year, the Mod II has been under development testing and is shown mounted in a test cell in Figure 2. The first engine began testing in January 1986 and, to date, has accumulated over 400 test hours. While engine failures did occur as expected, the basic engine has begun to demonstrate reliability and completed a full-characterization test in January 1987. The engine tested across a full range of speed and pressure, developing a maximum power level of 54 kW (72 hp) and a peak efficiency of 38%. Figures 3 and 4 show power and efficiency data, respectively, obtained from the first Mod II engine. The ultimate goal is for the engine system to provide 62 kW (84 hp) and a peak efficiency of 38.5%.

The Mod II was designed for installation in a GM Celebrity sedan. As equipped by GM, the Celebrity obtains 26 mpg in urban driving and 40 mpg in highway driving conditions, yielding a combined mileage of 31 mpg. With a Mod II Stirling engine installed, the Celebrity is projected to obtain 33 mpg in urban driving and 58 mpg in highway driving, yielding a combined mileage of 41 mpg. This is 32% above that of the spark-ignition engine. These mileage projections are based on experience with the Mod I Stirling engine, which provide confidence for the Mod II. All mileage quoted is for unleaded gasoline.

Comparisons of fuel economy alone can be misleading without a simultaneous comparison of vehicle performance. One criteria used to measure vehicle

performance is the time required for a car to accelerate from stop to 60 mph; the generally accepted automotive industry standard is 15 sec. Until recently, acceleration performance impeded Stirling engines from competing with spark-ignition engines. Stirling engines were excessively heavy and, therefore, exhibited poor transient characteristics relative to their weight. The Stirling engines used early in the ASE program performed poorly even though mileage data were reasonably competitive.

Figure 5 shows the progress made in vehicle performance and fuel economy over the course of the ASE program. Current fuel economy data on a Mod I Stirling engine-powered vehicle are 15% above that of a spark-ignition engine and vehicle performance has improved from an unacceptable 36 to 16 sec in a current Mod I Stirling-powered vehicle. This progress was made because of improved control system technology and a significant reduction in engine specific weight from approximately 14 to 5.5 lb/hp. The Mod II projections are consistent with this path of progress.

Three Mod II engines will be tested during the remainder of the ASE program to develop the technologies that will enable the engine to perform at a high enough level to achieve the technical goals of the program. Figure 6 illustrates a schedule for the remainder of the ASE program and depicts the engine development test plan and the point at which a Mod II engine will be installed and tested in a GM Celebrity. The program is expected to achieve its objectives by April 1988.

It should be emphasized that, although the program is scheduled to end in 1988, the funds used to cover costs are those appropriated for FY87. To understand this apparent contradiction, it is necessary to recall an incident that occurred in FY86. In early FY86, the administration deferred the release of appropriated funds identified for the ASE program. This deferral action was in effect for several months at a point in time when the program effort was concentrated on Mod II development. As a result, 12 professionals were laid off at MTI and work was cut back drastically, delaying Mod II development and moving the completion date for the program to the middle of 1988. In spite of the serious disruption to the program work effort, MTI replanned the program to adhere to our commitment to Congress to complete the ASE program with the appropriated FY87 funds.

During the past year, Mod I engines continued to develop useful life and reliability data while undergoing extensive testing. Figure 7 shows that during the past year, 2350 test hours were obtained on Mod I engines, bringing the total accumulated level to 16,750 hours. This is a drop from hours tested in the previous year and is consistent with the revised emphasis in the program from the Mod I to the Mod II. As stated earlier, the Mod II has accumulated approximately 400 test hours to date.

Such testing yields valuable information on the life and reliability of engine components. If industry and consumers are to accept the Stirling engine, they must be convinced of its life and reliability through thousands of test hours. Warranty claims and maintenance costs alone would be prohibitively high and prevent commercialization if a Stirling product were found to be unreliable.

It is important to emphasize that it is in the area of life and reliability that the request for a Stirling Technology Support effort be put in place in

FY88. When the ASE program goals are demonstrated with the Mod II engine, it will verify the performance potential of Stirling. However, there will be no demonstration of its life and reliability. It is necessary to continue to improve the technology as failures and problems are encountered in achieving life and reliability goals. To this end, the development effort will concentrate on Stirling heat input systems, seals, drive systems, materials, and controls.

One of the goals of the ASE program was to transfer Stirling engine technology to the United States. This has been accomplished in that this technology now resides with MTI. However, until such technology transfer is made to U.S. industry, it will not be of national benefit. To effect this transfer, a strategic initial step is to develop an engine manufacturer. This step has begun with the active participation of Deere & Company in the ASE program.

Through Deere & Company's involvement, detailed drawings were reviewed by a team of Deere manufacturing engineers with a goal of reducing engine manufacturing cost. This effort is still in progress and has already resulted in significant changes being proposed to reduce engine cost. As important, however, is the fact that the technology required to manufacture a Stirling engine has been transferred. In Deere & Company, the nation now has an organization familiar with the technologies and processses specific to Stirling engine manufacturing.

Again, this is an area where the need for a Stirling Technology Support effort has been identified. The technology necessary to reduce the manufacturing cost of the engine needs to be advanced further if the United States is to maintain its lead in Stirling engine capability.

STIRLING ENGINE DEVELOPMENT ACTIVITIES IN JAPAN

I personally visited Japan last year to assess firsthand the status of Stirling engine development activities there. It was known that a 6-year Stirling engine research and development project had been started in FY82 as part of an energy conservation program entitled the "Moonlight Project." This program is managed by Japan's Agency of Industrial Science and Technology through the Ministry of International and Trade Industry (MITI). Total funding is nearly 10 billion yen with the FY85 and FY86 budgets set at 1.673 billion yen ($10.4 million) and 2.231 billion yen ($13.9 million), respectively. The budget for the last year of the project in FY87 is not known at this time.

The objective of the Moonlight project is to develop 3-kW and 30-kW class Stirling engines with high efficiency, low emissions, and multifuel capability. Engine test demonstrations are to be made in FY87 for residential and commercial heating and air-conditioning applications and industrial and construction machinery applications, including electric power generation.

Four industrial companies are participating in this program: Mitsubishi Electric Corporation, Toshiba Electric Corporation, Aisin Seiki Company (a Toyota division), and Sanyo. Japanese universities and government agencies are also participating in the Moonlight project and include, as a minimum, Tokyo Institute of Technology, University of Tokyo, Agency of Science and Technology, and the National Aerospace Laboratory.

Of the four industrial companies, two represent a major threat to U.S. industry: Aisin Seiki (Toyota) and Mitsubishi. Both companies began developing Stirling engines prior to the Moonlight project, and both were instrumental in convincing their government to support and fund Stirling engine development. Each company indicated a commitment to commercialize Stirling engines.

Aisin Seiki is a member of the Toyota Group, which is composed of 12 other companies including Toyota Motor Corporation. Aisin Seiki employs 8800 workers and began to study Stirling engines in 1970. They have 65 people dedicated to the development of a 30-kW Stirling engine for commercial heat pumps under the Moonlight project. In addition, Aisin Seiki is developing a 50-kW Stirling engine for special vehicles with their own funds and have one engine installed in a car.

Mitsubishi is developing another engine design under the Moonlight project -- a 3-kW Stirling engine aimed at the residential heat pump market. At Mitsubishi, 25 people are dedicated to the development of Stirling technology, whereas, at MTI, we have less than 10 people dedicated to the development of engines in this size class.

INDUSTRY AND CONSUMER INTEREST

Over the last several years, MTI has been dedicated to transferring Stirling technology to U.S. industry, while simultaneously searching for paths leading to commercialization. Every effort has been made to obtain funds from other sources to support this work. Figure 8 depicts the various on-going activities MTI is pursuing to transfer Stirling technology to industry.

The thrust of these efforts has been directed at both transportation and stationary applications. In the area of transportation, a three-phase program to test and evaluate a Stirling-powered Air Force van for use in active flight line duty at Langley Air Force Base has been initiated (see Figure 9). The first two phases involve the use of a Mod I engine and the third phase calls for a Mod II engine. It is important to emphasize that although the demonstration involves a military van, it is the eventual commercial application that is most important. To this end, Deere & Company, the American Trucking Association, and Purolator Courier are actively participating in the program. Further, NASA and the U.S. Air Force are participating to assist in the orderly transfer of technology.

Currently, the program is approximately midway through Phase I, and 400 test hours are already accumulated on the van. Funding for the program is provided through the NASA Technology Utilization Office and to date represents $250,000, with total program funding expected to be $750,000.

Based on their impression of the Air Force van program and the advantages offered by the Stirling engine, the U.S. Postal Service recently requested a quote from MTI to manufacture and install 50 Mod II engines in postal vans for a fleet demonstration and evaluation program. In this effort, Deere & Company would manufacture the engines. MTI is now proceeding to develop this proposed program.

MTI has actively sought funds for two major markets in stationary applications: generator sets and commercial heat pumps. With regard to the

generator-set market, the U.S. Army has expressed an interest in a Mod II military generator set. Such a unit offers them an option for silent power, which is so critical in a battlefield environment. After discussion at the highest levels of the Army, MTI has submitted a proposal of several million dollars for a program to militarize a Mod II for Army generator sets.

With regard to the second market, commercial heat pumps, MTI has worked with Brooklyn Union Gas Company (BUG), Niagara Mohawk Power Corporation (NMPC), the Gas Research Institute (GRI), and Lennox Corporation. Proposals have been submitted to BUG and NMPC for demonstration programs within their districts to evaluate the feasibility of Stirling-powered heat pumps operating on natural gas as a fuel source.

CONCLUSIONS

The ASE program objectives and goals will be met as promised with the appropriated FY87 funds.

Interest in Stirling technology by U.S. industry is intensifying. End users are preparing budgets to conduct feasibility test and evaluation programs. As a minimum, the following list indicates those organizations who have expressed support for and an interest in Stirling technology.

American Trucking Association
Air Products and Chemicals Inc.
Brooklyn Union Gas
Cummins Engine Company
Deere & Company
Empire Generator Corp.
Gas Research Institute
Lennox Corp.
Newport News Shipbuilding
Niagara Mohawk Power Corporation
Purolator Courier
Syracuse University
University of Maine at Orono
U.S. Air Force
U.S. Army
U.S. Postal Service
Valmont Industries Inc.
Westinghouse Electric Corp.

By virtue of the ASE program successes, the United States is the world leader in Stirling technology. This advantage provides our nation with a core technology having a host of spin-off applications. These, in turn, can provide the United States with a greater capability for conserving energy, as well as maintaining the technological leadership in those areas. The significant technological advances made within the ASE program are summarized on Table 1.

The transfer of Stirling technology to an American engine manufacturer has begun. However, before substantial investments can be made to tool up and to develop new markets for a new engine like the Stirling, basic questions of manufacturability, manufacturing cost, field performance, market definition, and market acceptance must be answered. Although these issues require a time and resource investment, this process has been initiated by virtue of the involvement of Deere & Company in the ASE program.

Stirling activities in Japan represent a major threat to the leadership position of the United States. By virtue of accomplishments made in the ASE program, the United States currently possesses a technological leadership of several years over that of the Japanese designs. However, the dedication and resource commitment of the Japanese are aimed at three specific markets: special vehicles, heat pumps, and generator sets. Stirling technology must

continue to be advanced in the areas of performance, durability, reliability, and manufacturing cost in order for the United States to maintain its leadership in this technology of the future.

RECOMMENDATIONS

In summary, FY88 represents a transitional period whereby the United States stands at the forefront of a new technology. This technology is now being evaluated and assessed by an engine manufacturer and many end users for various applications. These applications fall into three general market categories: special vehicles, heat pumps, and generator sets. Stirling technology represents a viable alternative to power generation for this nation in the future when energy costs and environmental cleanliness will again be serious national concerns.

If the United States is to ward off a serious foreign challenge for leadership in Stirling technology, the technology must continue to advance. Although commercialization of this technology represents a long, costly path for American industry to initiate, plans to commercialize will evolve from the respective application evaluations and feasibility studies.

Therefore, Mr. Chairman, it is recommended that a Stirling Technology Support effort be initiated in FY88 as a follow-on to the ASE program. The goal of this effort would be to advance the level of technology for performance, life, reliability, and manufacturing cost. As summarized in Table 2, the technology development effort would focus on Stirling heat input systems, seals, drive systems, materials, and controls. It is requested that $8 million be authorized for this effort in FY88.

Thank you, Mr. Chairman, for the opportunity to appear before this important committee, and may I offer to answer any questions at this time.

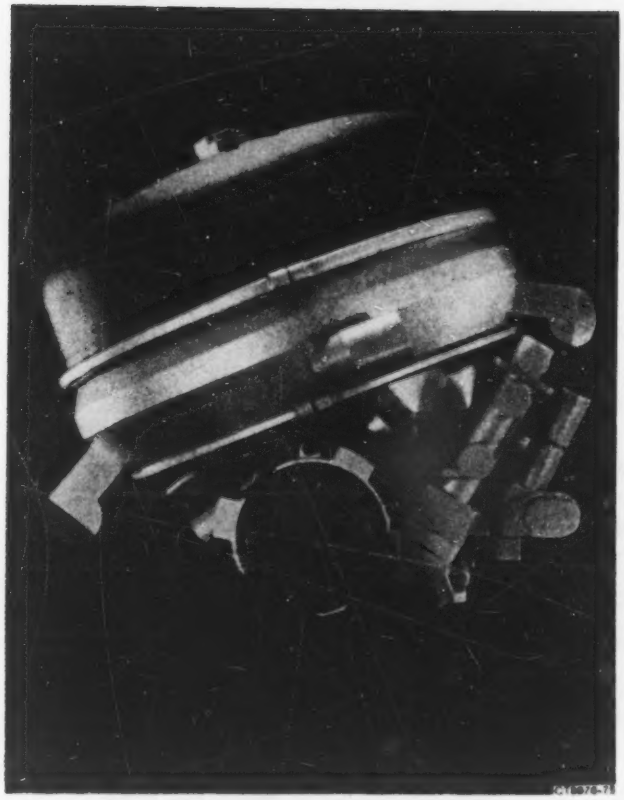


Figure 1 Mod II Stirling Engine - 80 hp

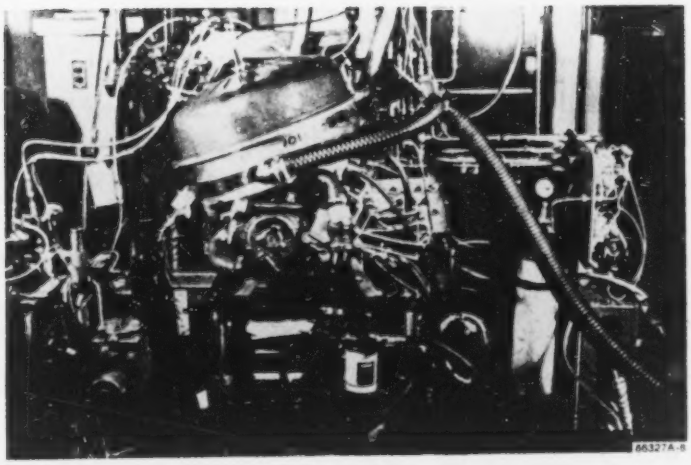


Figure 2 Mod II Engine Installation in a Test Cell

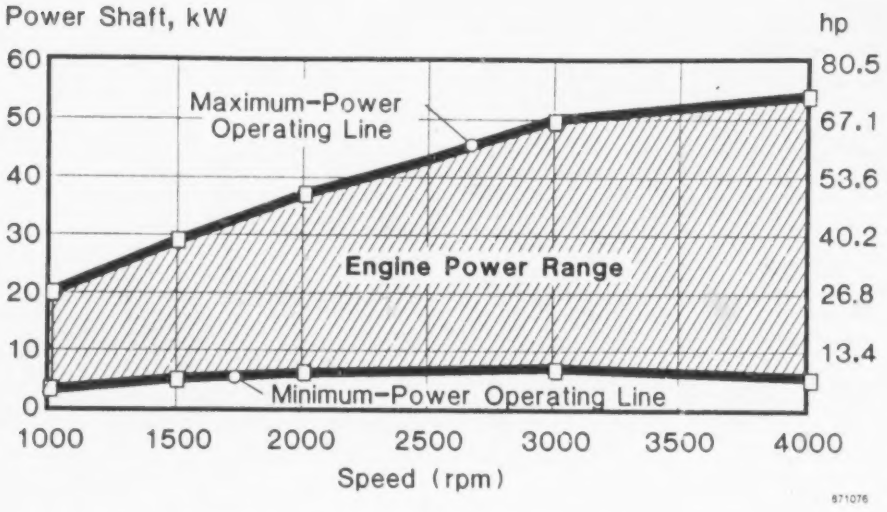


Figure 3 Mod II Basic Engine Power Data

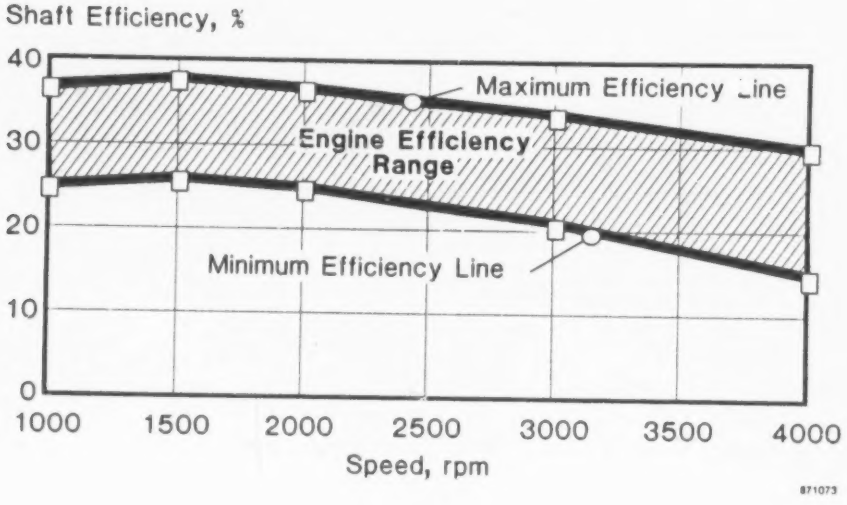


Figure 4 Mod II Basic Engine Efficiency Data

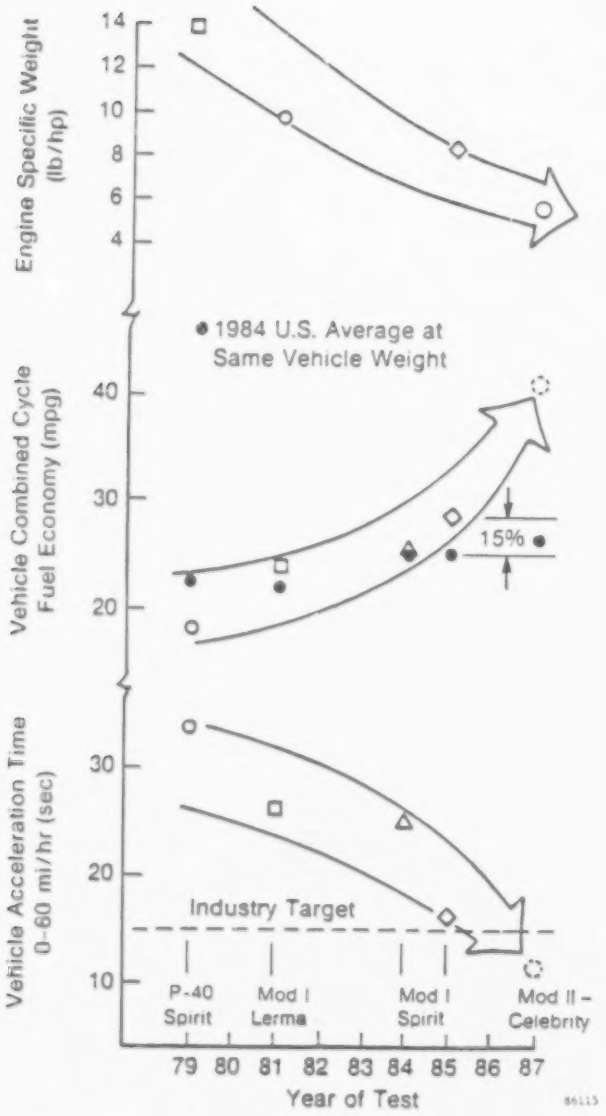


Figure 5 Automotive Stirling Engine Progress

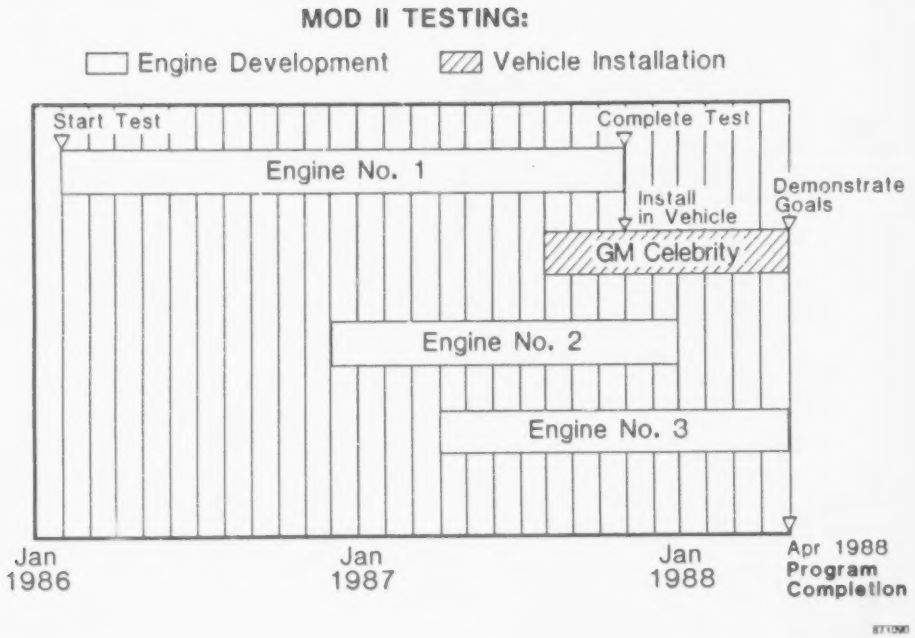


Figure 6 ASE Program Schedule

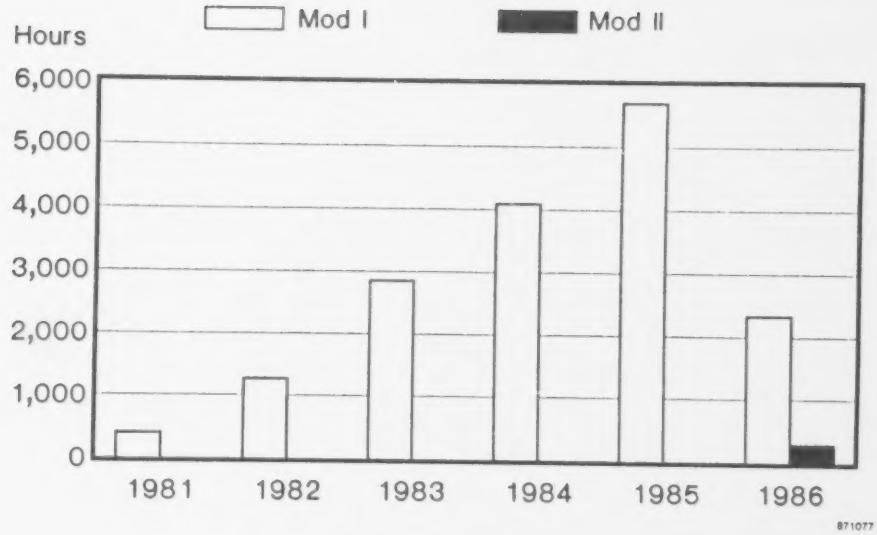


Figure 7 Stirling Engine Test Hours

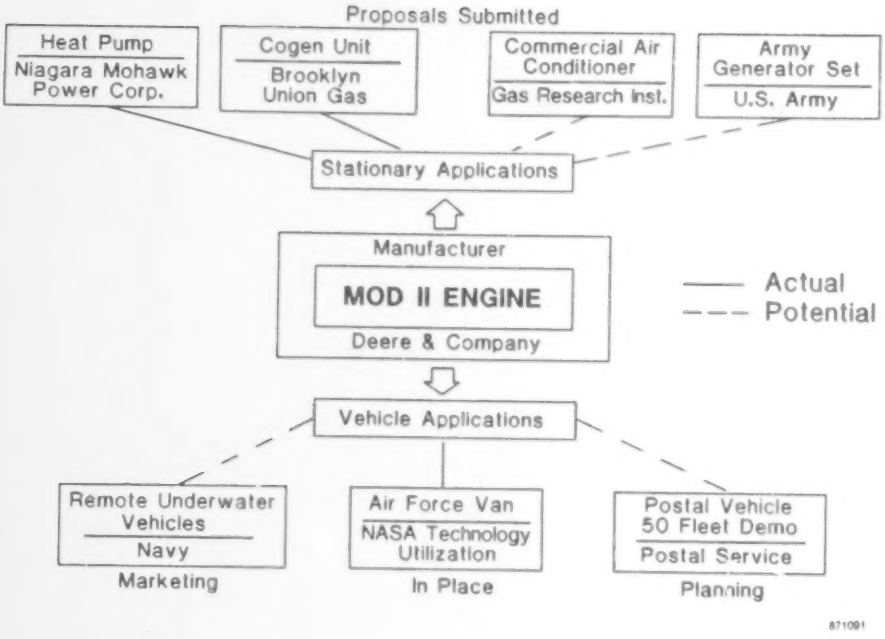


Figure 8 Stirling Application Activities

Figure 9 Stirling-Powered Air Force Van

Table 1

Automotive Stirling Engine Technology Progression

	Level of Stirling Technology	
	1978	1987
Fuel Economy		
EPA Combined Cycle (mpg)[1]	19	41
Vehicle Performance		
Acceleration 0-60 mph (sec)[1]	36	13
Emissions		
NO_x (g/mi)	0.40	0.32
HC (g/mi)	1.24	0.41
Engine		
Manufacturing Cost ($)[2]	Not Manufacturable	1200
Specific Weight (lb/hp)	14	5.5
Seal Life (hr)	100	2300
Strategic Materials	Cobalt	None

[1]3250-lb vehicle
[2]300,000 engines per year

Table 2

Stirling Technology Support Effort

Purpose

- Improve System Efficiency and Operational Performance
- Develop Life and Reliability
- Reduce Manufacturing Cost

Technologies

- Heat Input System
  - — Combustion System
  - — Heat Exchanger Components
- Seal Systems
  - — Rod Seals
  - — Piston Rings
- Drive System
- Materials
  - — Ceramics
  - — Low-Cost Materials
- Control Systems

Mr. MCCURDY. Very good. Mr. Gutgsell, why don't you spell your name for the recorder here?

Mr. GUTGSELL. G-U-T-G-S-E-L-L. I might add parenthetically that that picture of me driving that van evoked more than the casual interest of the Air Police as we parked under the 94th Airdrome Squadron. A civilian doesn't drive an Expediter van.

Deere & Company is, as you perhaps know, the largest manufacturer of agricultural equipment in the world, and one might wonder, why would we be involved in the Stirling engine?

In the process of manufacturing farm equipment, we have become the eighth largest manufacturer of diesel engines, and so therefore we find ourselves as a technology prime mover. We shall shortly be drawing together with our diesel manufacturing capability and those of General Motors to create an independent firm, perhaps the largest diesel manufacturer in the world.

We have been involved for a long time in advanced engine concepts, including the advanced diesel, the Score rotary engine, and the Stirling engine. The latter two, of course, are multi-fueled engines. We have had intensive studies in terms of alternative fuels, jet fuels, natural gas, soybeans, sunflower oil, ethanol, methanol, and we joined informally with the Stirling Engine Group some four or five years ago when we did a characterization on the Mod 1 Stirling engine up in our Product Engineering Center in Waterloo. And this culminated with a formal agreement with NASA, a Space Act agreement which we drew up in mid-1986 to participate with MTI, Purolater, and the American Trucking Association and NASA on the evaluation of the Stirling engine, which you saw pictured in the Expediter van.

We certainly concur with you, Mr. Hayes, that there is uncertain future for fuel, and we urge the continued federal presence in research and development and demonstration of alternative fuels and alternative fuel engines.

The Congress has wisely invested $120 million in the development of the Stirling engine. It represents a technology which is on the threshold now of manufacturing implementation.

We do know, however, that the automobile companies will not now adopt the Stirling engine, because it doesn't represent to them replicable manufacturing capability. So we join with Mr. Nightingale and MTI to urge that the DOE continue funding to facilitate continued work in this area.

We specifically suggest that maybe enhancement of the light van experiments under conduct at Langley would be appropriate, because we see that successful tests could stimulate orders. Those capable of ordering specific engine options as repowering occurs, specifically they might be such as the U.S. Post Office Department, which Noel suggested as an interested potential purchaser. The Purolater Courier Company and United Parcel firms might be others such as that.

We see the savings of billions of gallons of fuel, and at the 30 percent fuel efficiency that the engine currently enjoys, it might be advanced to something in the area of 55 to 60 percent.

As a potential Stirling engine manufacturer—and I must emphasize "potential" engine manufacturer of the Stirling—Deere is currently engaged in a Value Engineering value analysis of all the

parts and components of the Stirling engine. We are in the process of establishing manufacturing routings for this engine. Now these manufacturing routings may be used by us or any other engine manufacturer, but they do represent an actual study by those capable of manufacturing the engine. We shall develop accurate manufacturing costs.

Now these are funded in part—all of the aforementioned activities are funded in part by dollars that have come through MTI from NASA. Miss Fitzpatrick mentioned that Deere probably has committed $160,000 of its own funding. That might be minimal by some estimates, but we'll accept the $160,000.

But what we need to do to confirm the viability of Deere & Company as a manufacturer is to establish the commercial viability of the Stirling engine, which is yet to be done, and we need to determine the profit potential of the Stirling engine in the marketplace.

And so we concur with you, Mr. McCurdy, when you say that manufacturing technology is, indeed, research and development. So we urge all of you to please consider seriously the funding of continued endeavors for the Stirling engine.

Thank you.

Mr. McCURDY. Thank you, Mr. Gutgsell. I apologize for the interruption there.

Miss Fitzpatrick said early on—and I think this is a question for Mr. Nightingale and for you—that DOE has made the determination that this is not a viable project for automobile engines and that kind of technology. And obviously you disagree.

What do you think she or the Department bases that conclusion on?

Mr. NIGHTINGALE. Well, Mr. Chairman, I think the evaluation is centered on the automobile itself, and I don't think that we can argue with that. To fit the Mod 2 into the current cars that are on the road, with the sloping hoods and the very tight packaging requirements, the scaled-down front radiators, is the place where this technology, as it exists today, can be placed, I think that that is stretching the point a little bit too much, and I think that that's what her point is.

But the use of the engine in other vehicles is—in a special niche market, seems to be the place in which the penetration can occur, as is evidenced by some of the interests of the end-users.

So I think there's a distinction there in the word "automobile" to special trucks, vans, et cetera, versus the cars.

Mr. McCURDY. Thank you.

Dr. Powers, quickly has Ford lost its interest in the AGT, and why are you transferring the ceramic regenerator technology?

Dr. POWERS. In the AGT program, we were—the regenerator was our responsibility, so for Garrett to carry on, they need that, so we're transferring that.

If you look at Ford's history in turbines, basically we did a lot of work in the 1970s. When the DOE program started in 1979, we scaled down at that point. In fact, we were a subcontractor to Garrett in this program. And last year when ATTAP was being initiated, we took a hard look at the resources we have and what we think is doable by, say, the year 2000, and that's our main reason

for getting out, is that we want to focus on piston-type applications as opposed to turbine.

Mr. MCCURDY. At this point, I'm going to turn the meeting over to Mr. Hayes. Again, I have to apologize, especially to the next two witnesses. I will be back in a few minutes, but I have got the Minister of Finance from Guatemala sitting in my office. We've gone a little longer than we'd anticipated, and I need to take care of that very quickly, but Mr. Hayes will chair, and then have the next two witnesses appear, and we certainly want their testimony in the record, and he will conclude with questions to you.

Mr. Hayes.

Mr. HAYES [presiding]. All right. Let's decide how to split the money up. [Laughter.]

I want to mention to Mr. Helms that for 47 years my father has been a Buick dealer, and you have confirmed what he's always suspected, that Cadillacs are coal-operating vehicles. [Laughter.]

I'm going to mention that to him.

Mr. HELMS. I'll pretend like you didn't say that. [Laughter.]

Mr. HAYES. I don't know if—apparently I'm left without anyone to ask questions. I'm interested in one comment that was made earlier about the use of hydrogen. My understanding is—and please correct me—that the Mod 2 is hydrogen——

Mr. NIGHTINGALE. Yes, it is.

Mr. HAYES. Would you care to comment for me on the impression I got, though it wasn't dealt with in any detail, of there being a great, high safety risk in operating the Mod 2 for that reason?

Mr. NIGHTINGALE. If I can take some time to explain, because I think it's a misconception. I can break it into three parts.

First of all, it was an issue from the very, very beginning. There have been safety studies conducted by independent agencies on the safety of using hydrogen in the engine.

Second, the amount of hydrogen in the engine is probably no more than the size of that paper cup in front of you, and if it ever was ignited in total, at worst it would probably—it could break an eardrum. It's of that magnitude.

Now that's still very severe, but that never really happens. The fact is that hydrogen, when it—if it does ignite, does not produce a high flammable flame. We call it the Hindenberg Syndrome; the fact that over 90 people were involved in that accident, 60 of them lived, and the 30 who died did not die from burns, but basically died because they jumped, if you start to investigate into the dangers of hydrogen.

There are companies already in Germany and in Japan—and I can certainly supply you with some information on them—who are looking at hydrogen as a fuel, and they are talking about tanks of liquid hydrogen on the side of vehicles, with an eye to the future, of future alternative fuels, getting away from the liquid fuels.

So I guess I would have to say that the technology associated with handling hydrogen—and in this case, it's very, very small, as I've pointed out—can be had, as we obtained the technology to handle natural gas in homes, as we handled freon-22 in our refrigerators. There are methods that can be developed and instilled in the product to get at the safety issue.

I would not sit here and say to you that all of those safety issues have been addressed and are involved in the design as it exists today. I think there's a lot more to life and reliability and safety testing that we would have to conduct on the unit.

But we've brought it a long way. And I would say that my interpretation of the safety issue is more or less in the context of those three major areas.

Mr. HAYES. It seems to me that you've been put in an interesting dichotomy, as I understood the criteria of the Department of Energy. Either you have advanced through your research to the point where private industry should take over, at which time there should be no funding, or you haven't advanced to the point where private industry should take over, at which point there should be no funding because you haven't advanced.

Is there a possible third alternative, that you've advanced to a point where there is interest, and the interest expressed by some of the firms represented in this room this afternoon should be a basis for the continued funding of additional research to determine whether or not we can reach that third step, and that is independent commercial funding based upon feasibility of the product?

Is that what you're telling the committee this afternoon, that you've gotten to that point, and that the gentlemen here from John Deere and elsewhere reflect the merit of going forward.

Mr. NIGHTINGALE. Yes, I believe that's so, Mr. Hayes, that we're almost in a transitional period now where we're doing both, that we're executing with end-users and manufacturers, as John Deere is, to become familiar with the technology, understand it, and believe in it, and that's a very, very difficult process.

They want to see something in hardware. They want to test it themselves. They want to evaluate it themselves, and they want to see life and reliability.

At the same time, if we stop the fundamental work on the technology, then we will lose that lead that we have that's embodied in the Mod 2. And so I think that the technology support effort needs to go along in parallel with that effort, and it's very difficult for me to project for you—I don't know of anyone who can tell you when that line of commercialization will occur in the future, whether it's 12 months or 36 months from now. I can't say.

Mr. HAYES. Using that criteria that I just stated, of affirming from independent sources that we've reached the point, as you allege, where we then can justify funding on the basis of the next step, I assume that NASA must have done some kind of studies in connection with the van that you have operative; is that correct?

If so, what were the results of those studies? Have they done any kind of studies themselves, or has the military done any studies based upon their use in place of the van?

Mr. NIGHTINGALE. Studies by NASA per se on the use of the van, no, not as a vehicle. But the return on the technology, they have.

As you know—well, you don't know—we are also working with NASA on a space station application of the Stirling engine. They are very much in the space station. And so the technology flows into that direction, and they get to understand that.

In terms of the van application, NASA per se is not in the vehicle business, but they have brought together a team of vehicle interested parties—Purolater——

Mr. HAYES. I see.

Mr. NIGHTINGALE. And those studies have been conducted by those individuals, and in most cases, it's relative to reliability and life, rather than, you know, pure performance.

Mr. HAYES. I guess we have no one else with questions. We could perhaps have an audience participation, if we could——

[Laughter.]

Mr. HAYES. Or if we could ask, I think, Tom McMillen's attractive Administrative Assistant to spin a wheel, it would maybe add some color to the afternoon.

I guess we'll advance to the next panel, and Mr. McCurdy will get here in complete disarray, as I completely dismantle his semblance of order that he has in the subcommittee.

Thank you very much. I appreciate it.

Gentlemen, let me welcome you, and let me state for the record that—whoops, I can't state for the record. [Laughter.]

Dr. Vincent Halsall is the Vice President of the Advanced Battery Unit of Johnson Controls, Inc., and let me add to that, Mr. Sensenbrenner wanted to introduce you, since the company is located in Milwaukee, Wisconsin, but his schedule would not permit doing so. Let me, on behalf of Mr. Sensenbrenner, welcome you to our subcommittee hearing, and also mention the presence and later testimony of Dr. James Strang, the Director of Engineering, Environmental & Heat Transfer Systems Enterprise, AiResearch Manufacturing Company in Torrance, California.

STATEMENTS OF DR. VINCENT HALSALL, VICE PRESIDENT, ADVANCED BATTERY UNIT, JOHNSON CONTROLS, INC., MILWAUKEE, WI, ACCOMPANIED BY WILLIAM GENTRY; AND JAMES STRANG, DIRECTOR OF ENGINEERING, ENVIRONMENTAL AND HEAT TRANSFER SYSTEMS ENTERPRISE, AIRESEARCH MANUFACTURING CO. TORRANCE, CA

Mr. HALSALL. Thank you, Mr. Hayes. I would like to just introduce my associate, Bill Gentry, who will help me with this presentation.

Johnson Controls appreciates the opportunity to comment on the DOE's transportation program. We are aware of the Department's 1988 budget request to fund continuing research on batteries for electric vehicles and believe they fall significantly short of the technology support levels needed.

As background, JCI is the world's largest manufacturer of batteries. As a corporation of $2.7 billion, batteries are approximately 25 percent of our volume. [See correction Z in Appendix.] We employ 27,000 employees and do research work within the company to the tune of $39 million a year.

The growth of the Battery Division has occurred because of Americans' dependence on reliable vehicles. Further growth in the future is tied to questions of national concern, including that of the availability of oil. We need to continue to seek national energy independence. Developing alternatives requires money, and it re-

quires sustained effort from hardworking experts in the various fields of science.

We have become leaders in the world technology of the battery business by competitive efforts in a highly competitive world industry. We are trying today and tomorrow to stretch technology to develop new opportunities for energy storage.

For us as a battery manufacturer, electric vehicle batteries are a natural, though highly speculative, option. Batteries are the most critical performance-related component in the vehicle, as we have heard several times this afternoon. Battery development typically can take 10 to 20 years, and should there be a future crisis, it will likely be alternatives, not rationing, that the American public will seek.

Yet today, there is no incentive for private industry to develop alternatives like electric vehicle batteries, since there is no present existing or accurately predictable market for such a product.

With continuing support, however, we could be ready with those alternatives. At Johnson Controls, we are pursuing what we consider to be the most promising technologies for electric vehicle propulsion. These are primarily the advanced lead acid and zinc bromine battery systems.

To cover the lead acid system, we see this as a steadily moving target, baseline system. It is the system against which all other future advanced technology systems must be measured, but it is in no way static.

Investment of almost ten years and approximately $20 million, including government funds, has produced results in the lead acid electric vehicle battery development. We have gone from what was essentially a golf cart battery to a sophisticated, state-of-the-art unit, the EV-2300, with high specific energy and long discharge cycling capability.

To make these improvements, we had to overcome a number of obstacles. A major problem was that concentrated acid would collect on the bottom of the battery as it operated. This led to the dissolution of plates and the destruction of the battery. By developing an integral acid circulation technique, using the principle of introducing pressurized pulses of air in a novel pumping system, we not only eliminated acid stratification, but improved the unit's current performance and cycle life. The battery displays both improved power capability, and the active mass of the battery itself is better utilized.

A further obstacle has been weight. One major answer was our development of what we call the "combo-grid." By replacing some of the lead support structure in the battery grid with plastic, we reduced the weight in some grids by as much as two-thirds and were able to significantly increase the battery's specific energy.

The next problem, which we are now addressing, is one of the toughest. With standard designs, the acid is unable to penetrate the active materials and reach those active sites where the electro chemical reaction takes place. As a result, the electric vehicle hauls the weight of all the material, but it doesn't benefit from total usage of that material.

We are attacking this problem in our current four-year DOE-funded development program, which we started in 1986. Our direct

solution is to push the acid through the battery plates, so that more of their mass can be utilized during every part of the cycle. We call this the "flow-through concept," and using the EV-2300 design as a baseline, dramatic improvements are being seen.

Tests made last November at the Argonne National Labs, which monitors our progress, showed an improvement of 40 percent in the utilization of materials. More recently, in-house tests have shown that utilization has been increased up to 63 percent.

We can translate these gains to mean that a battery will exhibit a specific energy of 53 watt-hours per kilogram, an increase of 89 percent over our baseline product. This progress certainly suggests that we will be able to meet or surpass the program's specific energy goal of 56 watt-hours per kilogram in a total vehicle propulsion battery. I stress this latter, because the 53 watt-hours per kilogram previously discussed refers to a single unit, as opposed to an entire operating vehicle battery system.

Our scheduled work for the future is to increase the utilization of active materials and to perform the development of various subsystems, the thermal management and the acid circulation package that support the entire system.

We are confident that we can meet the goals of this program, as we have met the goals of prior programs where we have undertaken developments. We have a team in place, making good progress, and need continuity of support. We need about three years of cost-shared funding of approximately $1 million a year to accomplish this.

I would comment that the battery that Mr. Streb referred to earlier in the day as having proved itself to be a successful electric vehicle battery, the gel-cell, is, in fact, a battery that was commercialized within JCI approximately five years ago with a prime intention of lowering the maintenance needs. But it doesn't yet offer anything approaching the yield capabilities which are being demonstrated in the present programs.

In the next area of technology, that of zinc bromine, in 1982 Johnson Controls acquired rights to the technology behind the zinc bromine battery chemistry from Exxon Corporation. The combination of our manufacturing expertise and our strength in electro chemical technology, coupled with the broad foundation provided by Exxon's prior efforts, has promised rapid progress in developing the battery for commercialization.

Manufacturing cost projections for the zinc bromine battery and its performance characteristics show it to be a likely attractive electrical vehicle option for propulsion purposes.

The many technical problems—and I should say, there are many in this battery—are being addressed by ourselves, and we are sharing some of our information with international partners in Japan and also in Europe, although we are doing this from a very selfish level, in that we believe that we are picking up significant sharing advantages to ourselves.

Significant levels of basic materials research and systems development efforts are being pursued in order to make further gains in the battery's performance and reliability.

Our zinc bromine technology does have several unique advantages. The almost all-plastic construction has weight and manufac-

turing cost advantages compared to other zinc bromine and other non-lead acid battery systems, and Johnson Controls is one-third operational with an entire Plastics Division; therefore, we sit with a considerable variety of this type of expertise in-house.

In addition, the modular system design and the complexation of the active bromine, external storage of the stable electrolyte, and ambient temperature operation, as opposed to the high or refrigerated temperature systems which are competitive, together with its high-voltage stack design, give, in our view, a fairly obvious advantage to this application in an electric vehicle.

Johnson Controls has started work on a three-year $2.7 million program with Sandia National Labs to develop the zinc bromine battery for use in an electric vehicle. The result will be a long-life, high-power battery for a light van. This program implements the materials and fabrication concepts from past development efforts, internally funded, and adds improvements from our continuing research in systems engineering.

As a baseline, we last year modified an electric powered van from one of the Johnson Controls fleets and began to show it to management as a potential test bed for Johnson Controls, Inc. bromine batteries. This test bed should allow us to get the battery out of the lab and into operating use.

We have set ambitious goals in our zinc bromine program. They are to demonstrate consistent battery life in excess of 1000 deep discharge cycles, to demonstrate a battery that has a specific energy of at least 70 watt-hours per kilogram, a specific power of at least 120 watts per kilogram, and to achieve energy efficiency of better than 70 percent.

We think the battery is capable of reaching these goals and reaching them at an estimated manufacturing cost of approximately $55 per kilowatt hour, which would make them indeed economical in a light vehicle application.

We estimate this program will require three to four years of shared funding at a level of approximately $1.2 to $1.4 million a year.

In general, I would like to comment that our work with the Department of Energy and the National Laboratories is central to both our lead acid and zinc bromine advanced efforts. We are pleased with the results of the cooperation and believe that they are, too. We look forward to continuing this relationship with these organizations, and Johnson Controls continues to be willing to work in cost-shared relationships.

Once these technologies have been proven through cooperative effort, JCI will bring them to commercialization through the new operating unit of the company, termed our Advanced Battery Business Unit, which I head and whose purpose from corporate charter is to develop, manufacture, and market promising technologies for a variety of applications, including that of electric vehicles.

I would mention that as a competitive entry, Johnson Controls makes Ford and Chrysler, our existing customers, very much aware of our efforts. The level of effort that is being defined in these programs is truly the minimum critical level. There is a critical mass below which you can't effectively pursue programs. We think this is important in reviewing budget needs.

In conclusion, we would like to reiterate that we strongly support the government sector continuing to take an active role in assisting private industry in developing battery systems for EVs. JCI is ready to support the industry, as and when it develops. Any loss of continuity now would be seriously detrimental to the development path. Certainty of support, having the assurance that our work today can be carried on, is critical.

I thank you for giving these views your attention. Thank you, Mr. Hayes.

[The prepared statement of Dr. Halsall follows:]

The DOE Transportation Program and its FY 88 Budget

Presented to the
Subcommittee on Transportation, Aviation and Materials
Committee on Science and Technology
U.S. House of Representatives

by
Vincent M. Halsall
Vice President and General Manager
Advanced Battery Business Unit
Johnson Controls, Inc.

March 3, 1987

JOHNSON CONTROLS, INC. TESTIMONY
MARCH 3, 1987

Johnson Controls appreciates this opportunity to comment on the Department of Energy's Transportation Program. We support the department's 1988 budget requests to fund continuing research and development of batteries for electric vehicles.

When we look at the progress and outlook for the electric vehicle battery, we need to ask three questions:

Why develop a battery at all?
Why do it now?
How do we do it effectively?

Johnson Controls is the world's largest manufacturer of automotive batteries. Therefore, the ability of American citizens to use personal transportation is very important to our company. If they don't use cars, Johnson Controls can't sell batteries. That would concern us because our battery sales in the domestic market represent 20% of Johnson Controls' consolidated revenue.

Our business has grown because of Americans' dependence on their vehicles. Further growth is tied to questions of national concern about the availability of oil. We have already passed through one oil crisis. Some experts are predicting another one, even more severe than the first.

Our way of life in this country is driven by our personal vehicles. Will we be able to afford to keep pumping our valuable oil resources into these vehicles or should we use foresight in developing alternative power before the next crisis?

Developing alternatives requires money and it requires expertise. We have become leaders in the battery business primarily because of our technological leadership. Maintaining leadership requires stretching that technology beyond the status quo to develop new opportunities for energy storage. For us as a battery manufacturer, electric vehicle batteries are a natural though highly speculative option.

This brings us to the second question - why develop an electric vehicle battery now? The answer is simple. Batteries are the most critical performance-related component in the vehicle. Battery development can take 10 to 20 years. Petroleum shortages or pricing pressures develop much more quickly. If we look at recent history, we have a sobering reminder that - it can indeed happen here - almost over night. And should there be a future crisis, it will be alternatives, not rationing, that Americans will seek. Yet today there is no incentive for

private industry to develop alternatives like electric vehicle batteries, since there is no existing or accurately predictable market for such a product.

With your continuing support, however, we can be ready with those alternatives. At Johnson Controls, we are pursuring what we consider the most promising technologies for electric vehicle propulsion: The lead acid and zinc bromine battery systems.

LEAD ACID

The investment of almost ten years and approximately $20 million, including government funds, has produced results in lead acid electric vehicle battery development. We have gone from what was essentially a golf cart battery to a sophisticated, state-of-the-art unit (the EV-2300) with high specific energy and long discharge cycling capability. To make these improvements, we had to overcome a number of obstacles.

A major problem was that concentrated acid would collect on the bottom of the battery as it operated. This led to the destruction of the battery. By developing an acid circulation technique using the principle of introducing pressurized pulses of air into a novel pumping system, we not only eliminated acid stratification, but improved the unit's performance. The battery displayed improved power capability and the active mass of the battery was better utilized.

Another obstacle was weight. One answer was our development of what we called the "combo-grid." By replacing some of the lead support structure of the battery grid with plastic, we reduced the weight and increased the battery's specific energy. The next problem, which we are now addressing is one of the toughest. It is an electrochemical phenomena that limits the performance of the battery. With standard designs, the acid is unable to penetrate the active materials and reach those sites where the electrochemical reactions take place. As a result, the eletric vehicle hauls the weight of all of the material but does not benefit from the total mass.

We are attacking this problem in our current four year DOE development program started in 1986 and monitored by Argonne National Labs. Our solution is to push the acid through the battery plates so that more of their mass can be utilized. We call this the "flow-through concept." Using the EV-2300 design as a baseline, dramatic improvements are being seen. Tests made last November at Argonne National Laboratory showed an improvement of 40% in the utilization of the materials. Recently, in-house tests have shown that the utilization has been increased by 63%. We can translate these gains to mean that a battery will exhibit a specific energy of 53 Wh/kg, an

increase of 89% over the EV-2300 baseline product. This progress suggests that we will be able to meet or surpass the program specific energy goal of 56 Wh/kg in an EV propulsion battery.

Our scheduled work for the future includes additional increases in the utilization of active materials and the development of various subsystems, thermal management and acid circulation, that support the battery system. We are confident that we can reach the goals of this program as we have met the goals of the earlier ones. We have the team in place, making good progress and need continuity of support. We need about three years of cost shared funding of approximately $1 million a year to accomplish this.

ZINC-BROMINE

In 1982, Johnson Controls acquired the rights to the technology behind the zinc bromine battery system from Exxon. The combination of our manufacturing expertise and our strength in electrochemical technology, coupled with the broad foundation provided by Exxon's prior efforts, promised rapid progress in developing the battery for commercialization. Manufacturing cost projections for the the zinc-bromine battery and of its performance characteristics show it to be attractive for electric vehicle propulsion.

The many technical problems of this battery are being addressed. Significant levels of basic materials research and systems development efforts are being pursued in order to make further gains in the battery's performance and reliability. Our zinc-bromine technology has several unique advantages. The nearly all-plastic construction has weight and manufacturing cost advantages compared to other zinc-bromine and the other non lead acid battery systems. The modular system design, complexation of active bromine, external storage of the stable electrolyte, ambient temperature operation, and the high voltage stack design give the technology an obvious application in an electric vehicle.

Johnson Controls has started work on a three-year $2.7 million program with Sandia National Laboratory to develop the zinc bromine battery for use in an electric vehicle. The result will be a long-life, high-power battery for a light van. This program implements the materials and fabrication concepts from past development efforts and adds improvements from our continuing research and systems engineering. As a baseline, we have modified an electric powered van to serve as a test bed for JCI zinc-bromine batteries. This test bed will allow us to get the battery out of our lab and into operating use.

We have set ambitious goals in our zinc-bromine program. They are to demonstrate consistent battery life in excess of 1,000 deep discharge cycles; to demonstrate a battery that has a specific energy of at least 70 watt-hours per kilogram, a specific power of at least 120 watts per kilogram, and to achieve energy efficiency of over 70%. We think the battery is capable of being developed to reach these goals, and reach them at an estimated manufacturing cost of $55/kWh that would make them economical in electric vehicles. We estimate this program will require three to four years of shared funding at a level of approximately $1.2 to $1.4 million per year.

Our work with the Department of Energy and the National Laboratories is central to both our lead acid and zinc bromine activities. We've are pleased with the results of that cooperation, and believe that they are too. We're looking forward to continuing our relationship with these organizations on a cost-shared basis. Once these technologies have been proven through our cooperative efforts, Johnson Controls will bring them to commercializastion through a new operating unit of the company. Called the Advanced Battery Business Unit, its purpose is to develop, manufacture and market promising technologies for a variety of applications, including electric vehicles.

In conclusion, JCI wants to reiterate that we strongly support the government sector continuing to take an active role in assisting private industry in developing battery systems for electric vehicles. JCI is ready to support the electric vehicle industry when it develops. Any loss of continutiy now would be seriously detrimental to the development path. Certainty of support - having the assurance that our work today can be carried on - is critical.

Thank you for giving these views your consideration.

73-573 O - 87 - 8

February 20, 1987

BIOGRAPHY

VINCENT M. HALSALL, born December 12, 1931 in United Kingdom

Became U.S. Citizen 1969

Education

Associate of the Royal Institute of Chemistry - London, England, 1955
Fellow of the Royal Institute of Chemistry - London, England, 1962

Positions at Johnson Controls, Inc.

Joined Johnson Controls in 1964
Senior Development Engineer, Battery Division, 1964
Manager, Product Engineering, Battery Division, 1967
Manager, Engineering Operations, Battery Division, 1972
Vice President, Engineering, Battery Division, 1973
Vice President and General Manager, Advanced Battery Business Unit, 1986

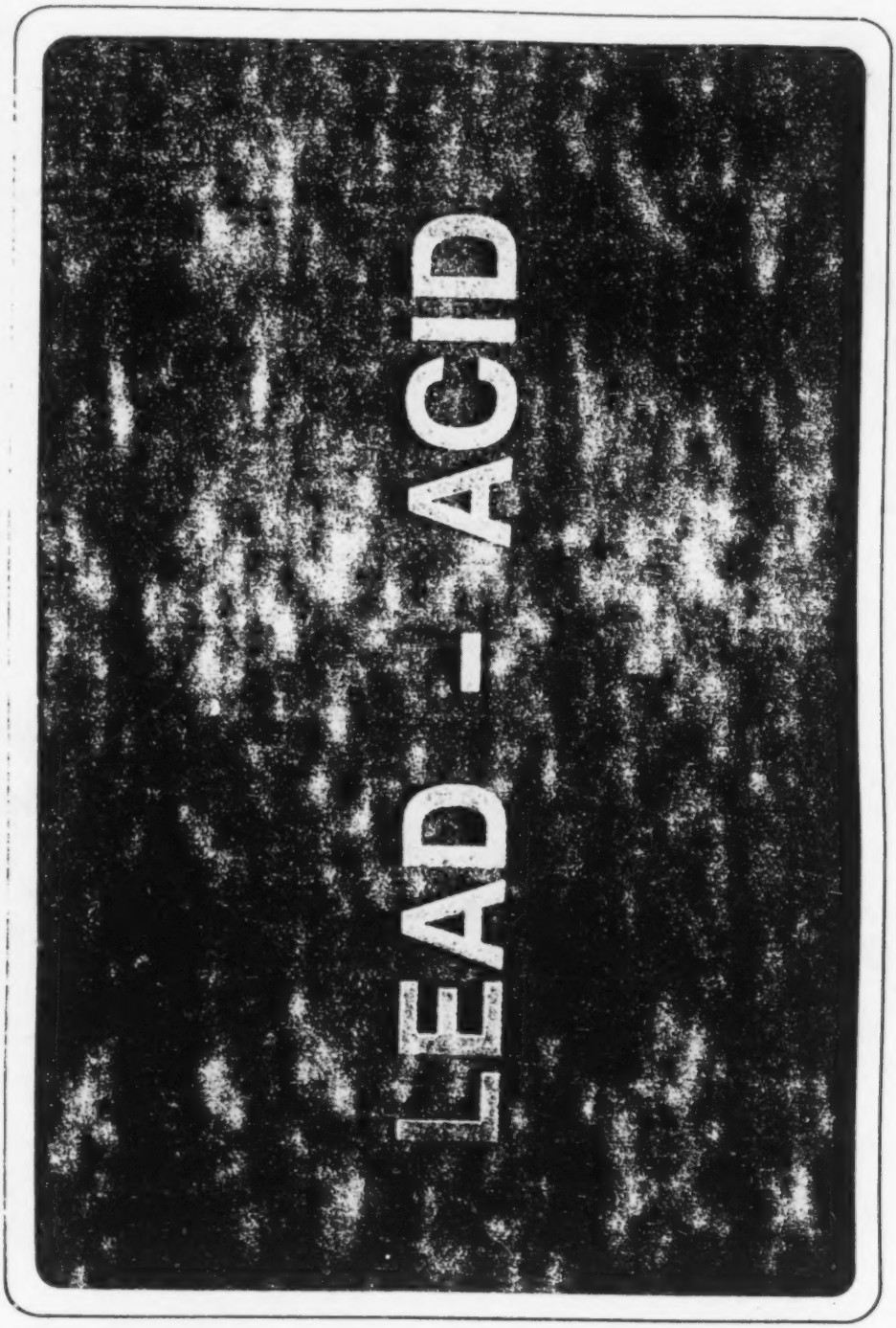
Work Experience

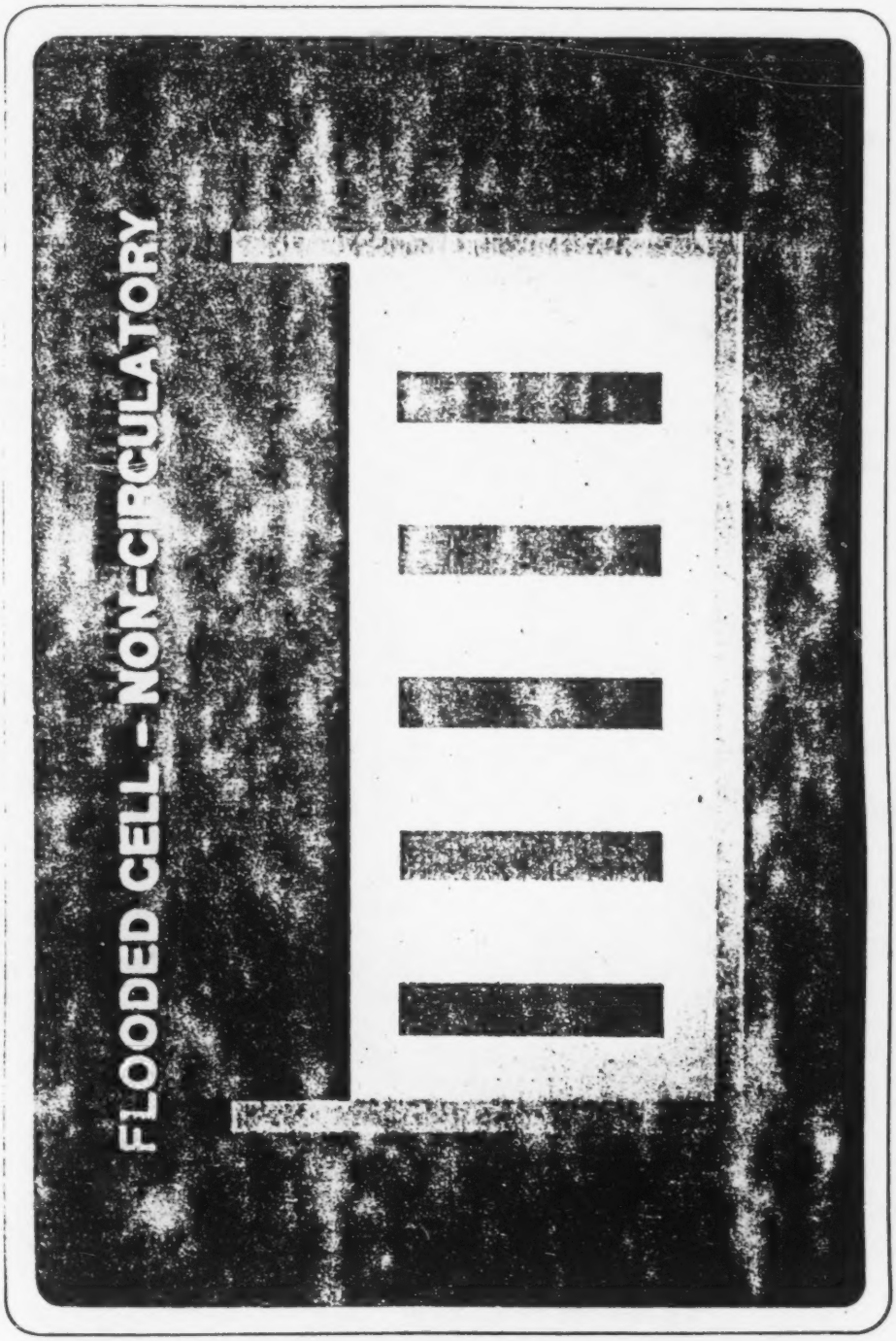
Chloride Electric Storage Co., England - Battery Research
Hart Battery Co., Ltd., Quebec, Canada
Electric Storage Battery Co., Ltd., Ontario, Canada

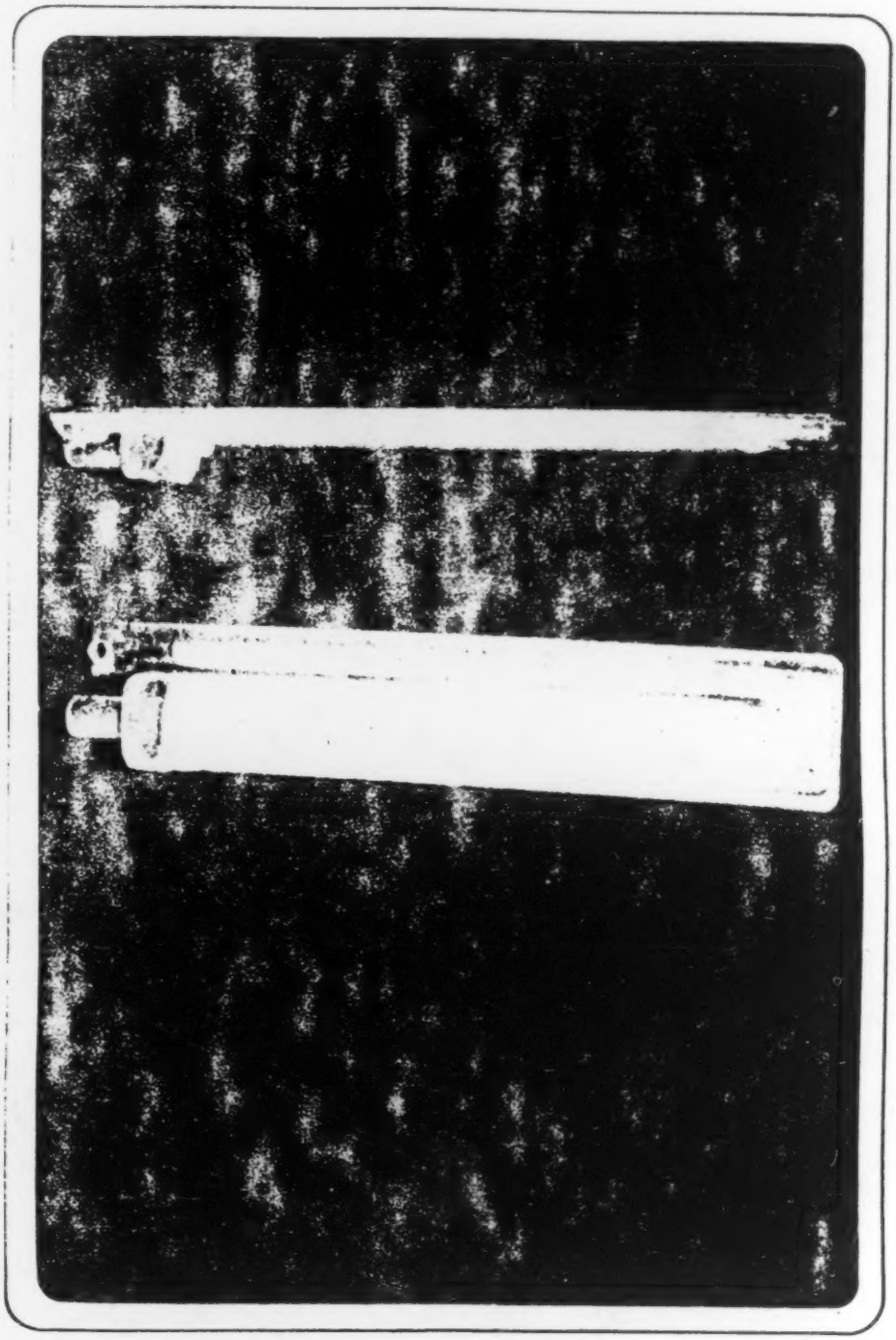
Professional Activities

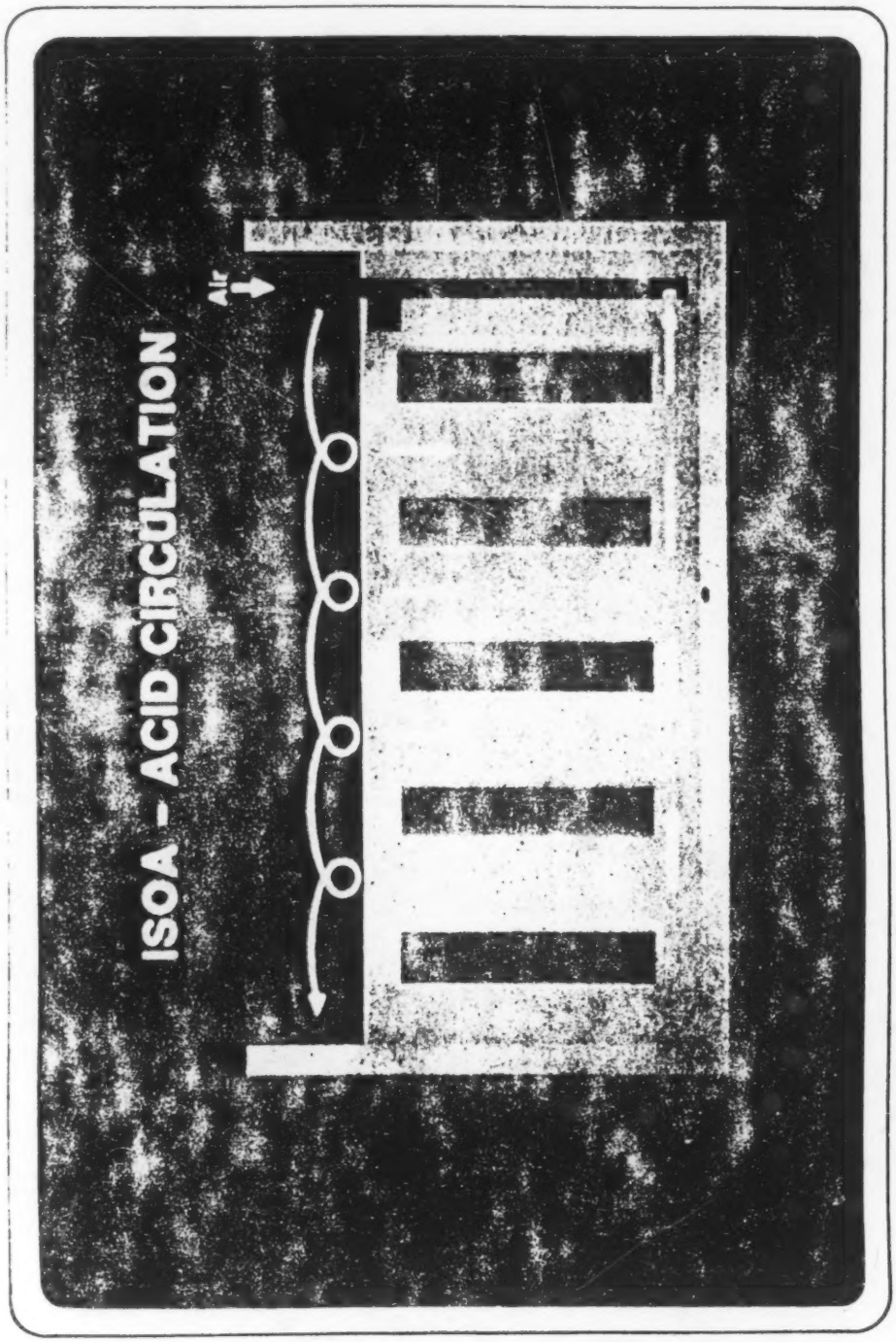
Chairman Battery Council International Technical Committee
Society of Automotive Engineers
Institute of Chemical Engineers
Royal Institute of Chemistry

Author/co-author of nine patents relating to batteries.
Author/co-author of many published papers.

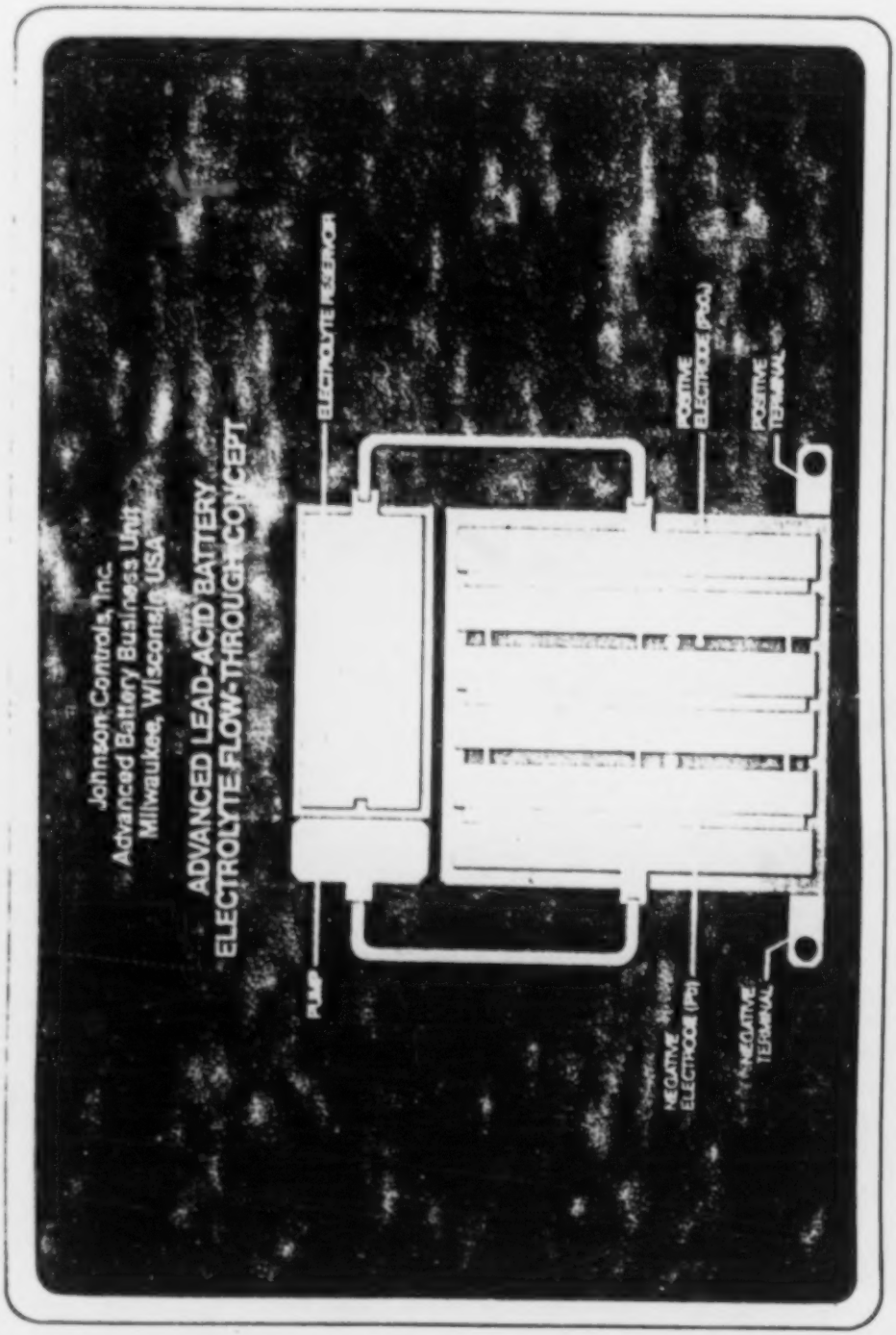

LEAD - ACID


FLOODED CELL - NON-CIRCULATORY

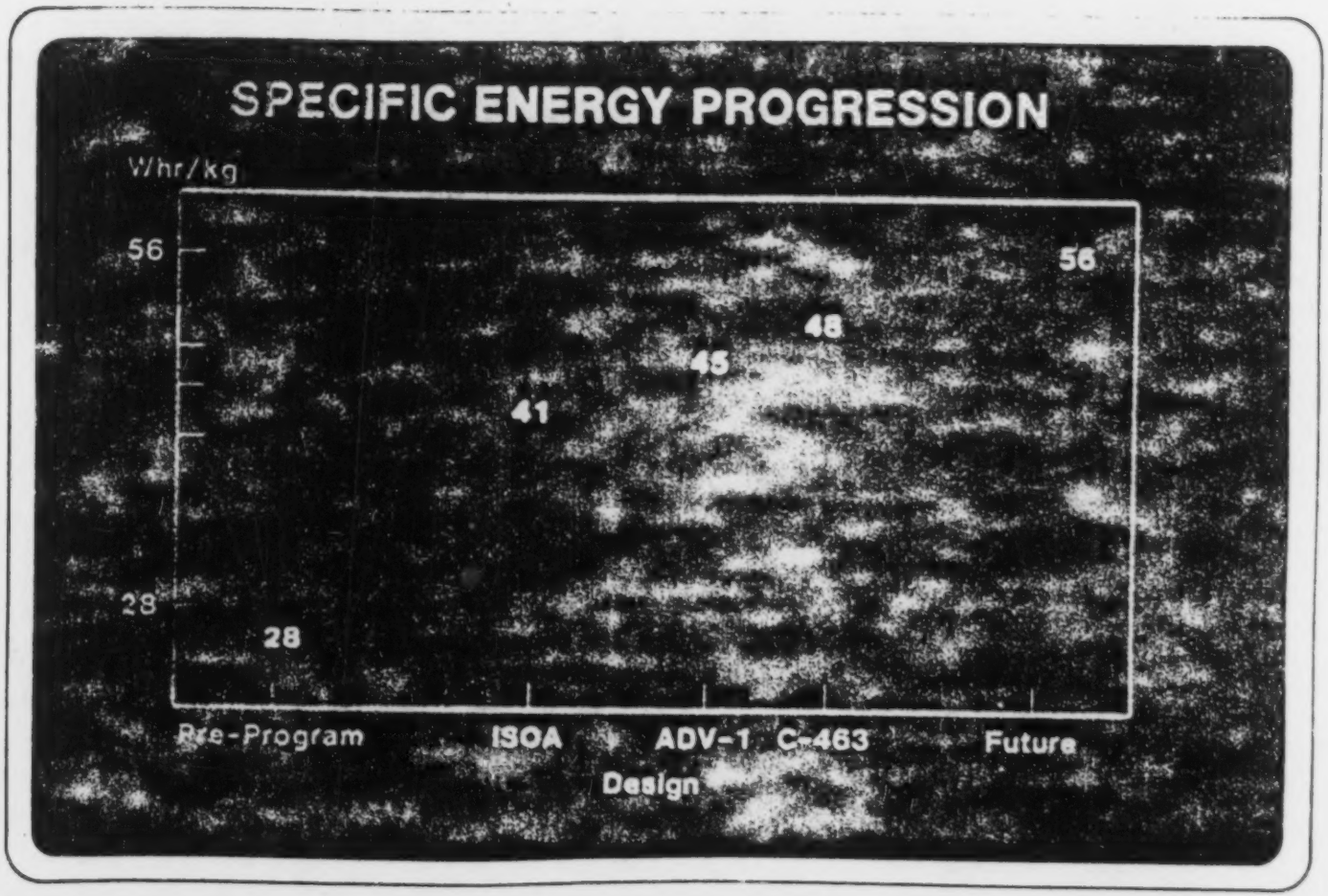


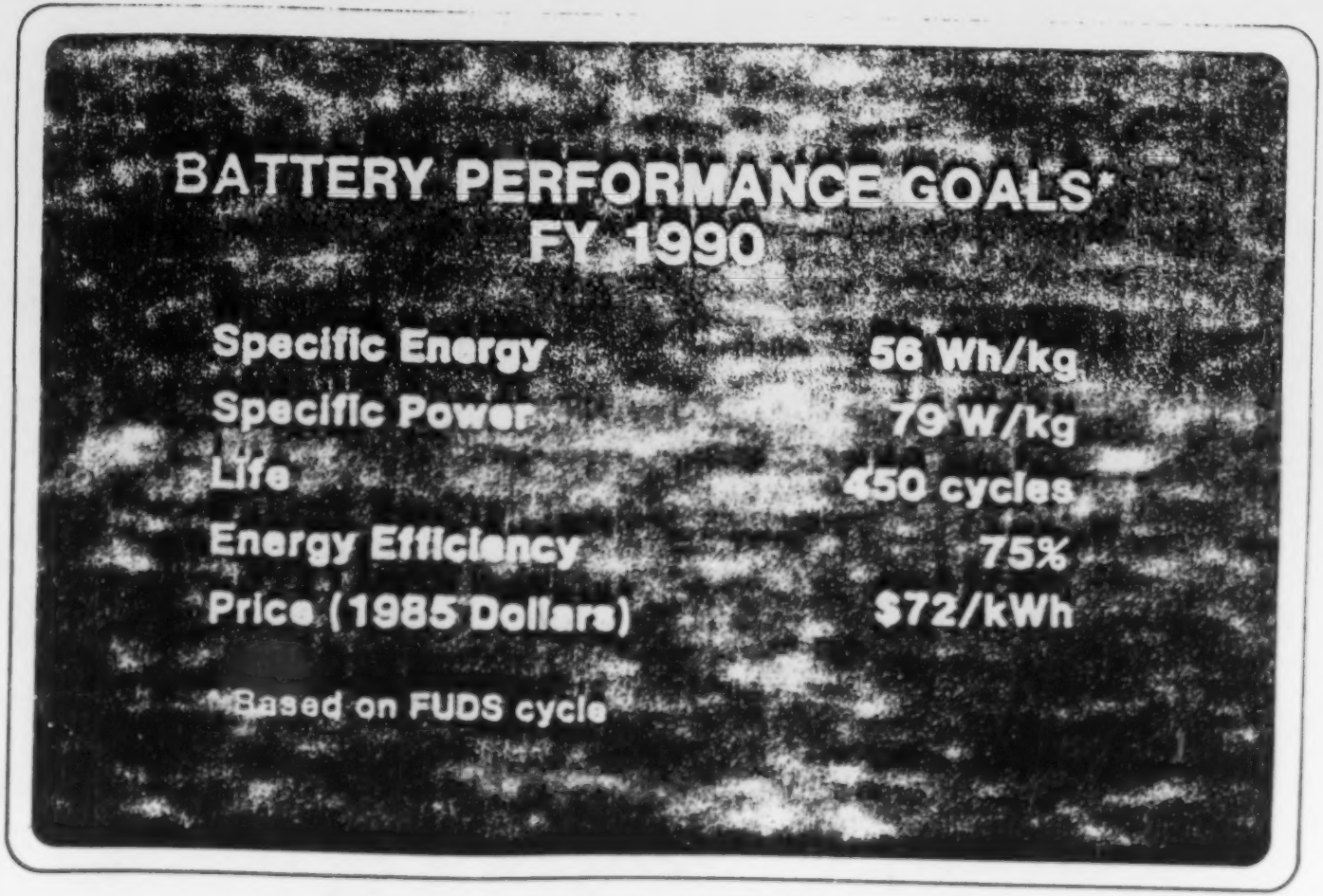

ISOA - ACID CIRCULATION
Air

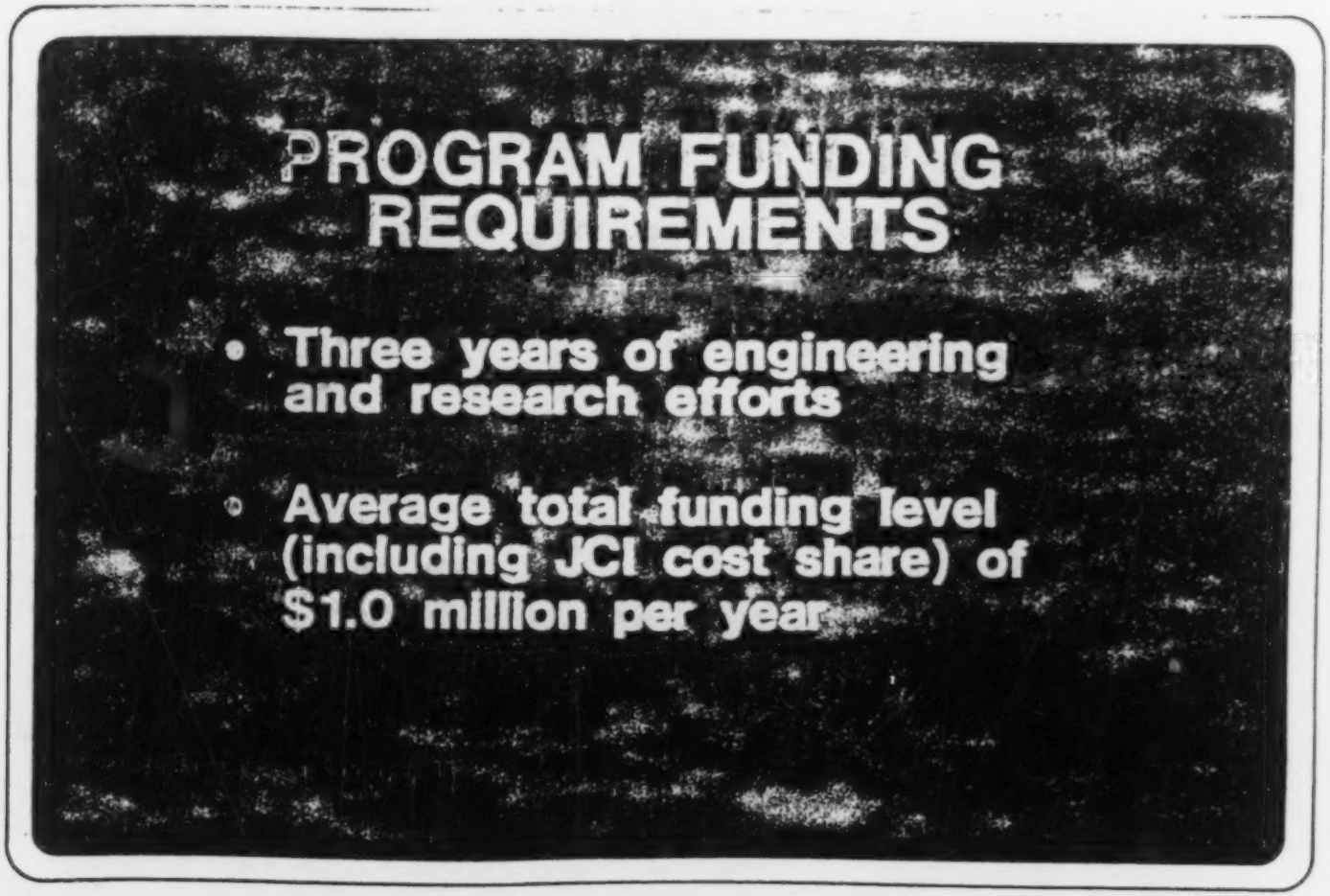
COMBO POSITIVE
BRANCHED RADIALS


Johnson Controls, Inc.
Advanced Battery Business Unit
Milwaukee, Wisconsin, USA
ADVANCED LEAD-ACID BATTERY
ELECTROLYTE FLOW-THROUGH CONCEPT
ELECTROLYTE RESERVOIR
POSITIVE ELECTRODE (PbO2)
POSITIVE TERMINAL
PUMP
NEGATIVE ELECTRODE (Pb)
NEGATIVE TERMINAL

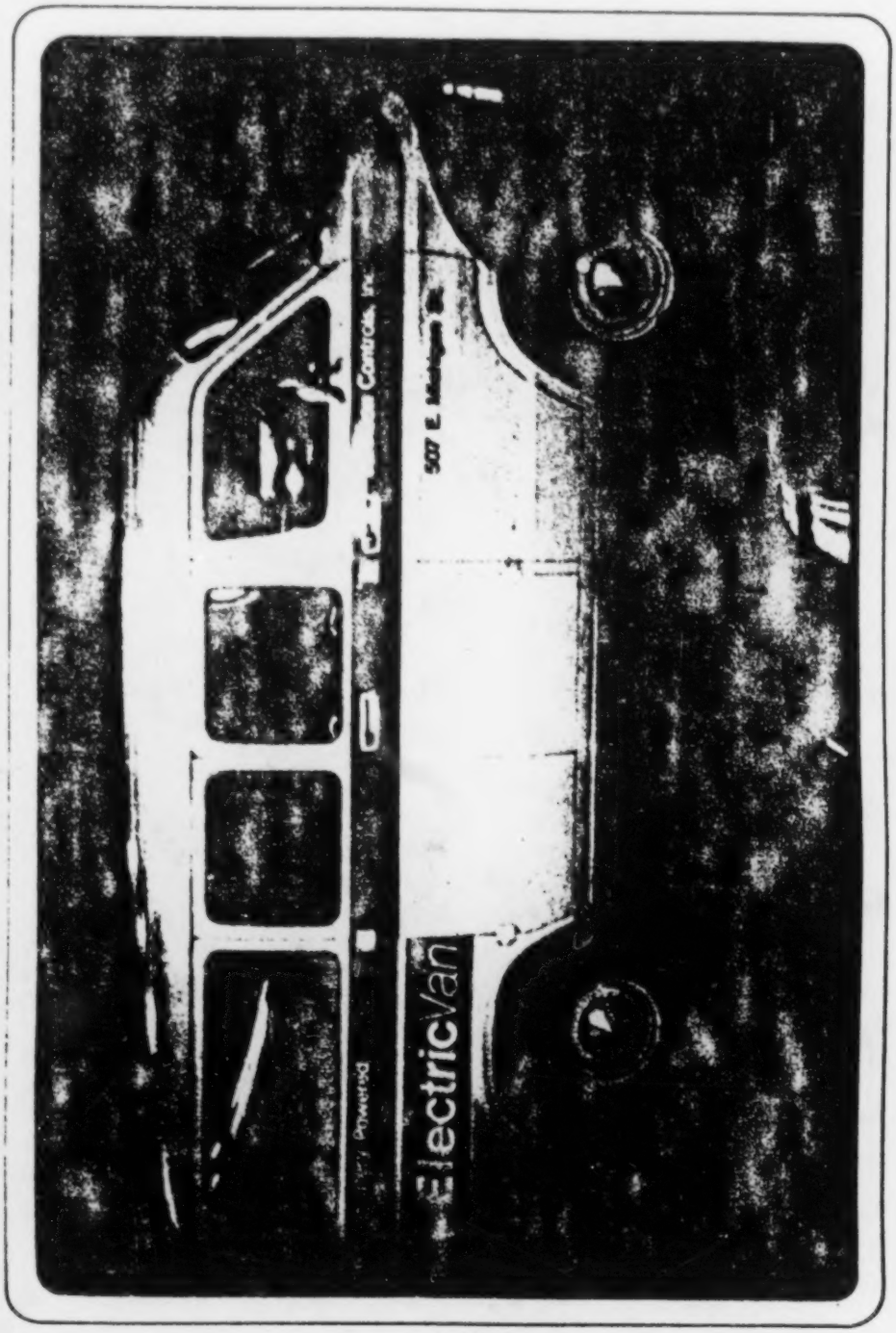
POSITIVE ACTIVE MATERIAL UTILIZATION
(AMPERE-HOURS PER POUND)
60.0
48.4
42.7
30.6
+58.0%
+39.5%
EV-2300
C-450 First Deliverable
C-483

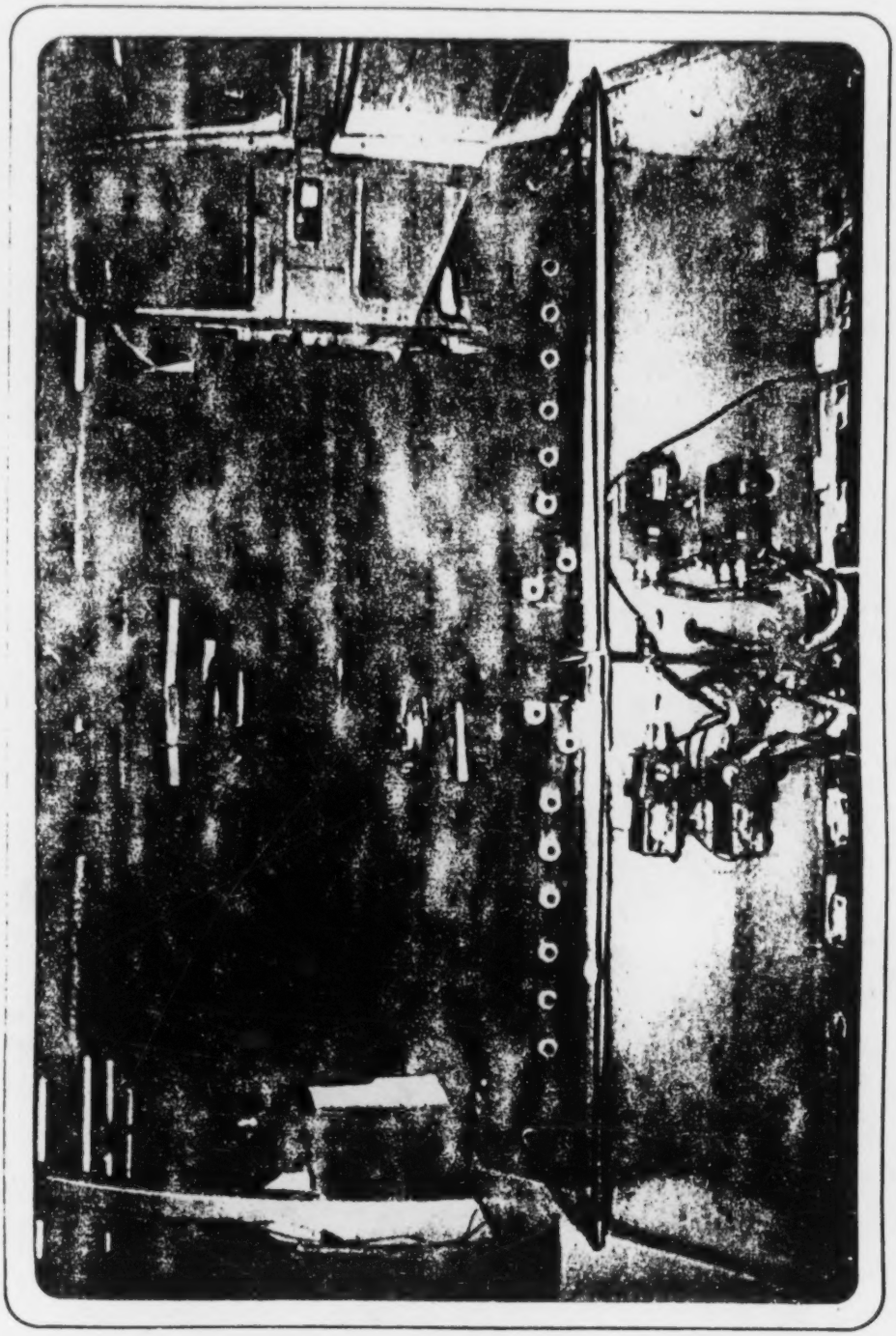

SPECIFIC ENERGY PROGRESSION
Whr/kg
56
28
56
48
45
41
28
Pre-Program
ISOA
ADV-1
C-463 Design
Future

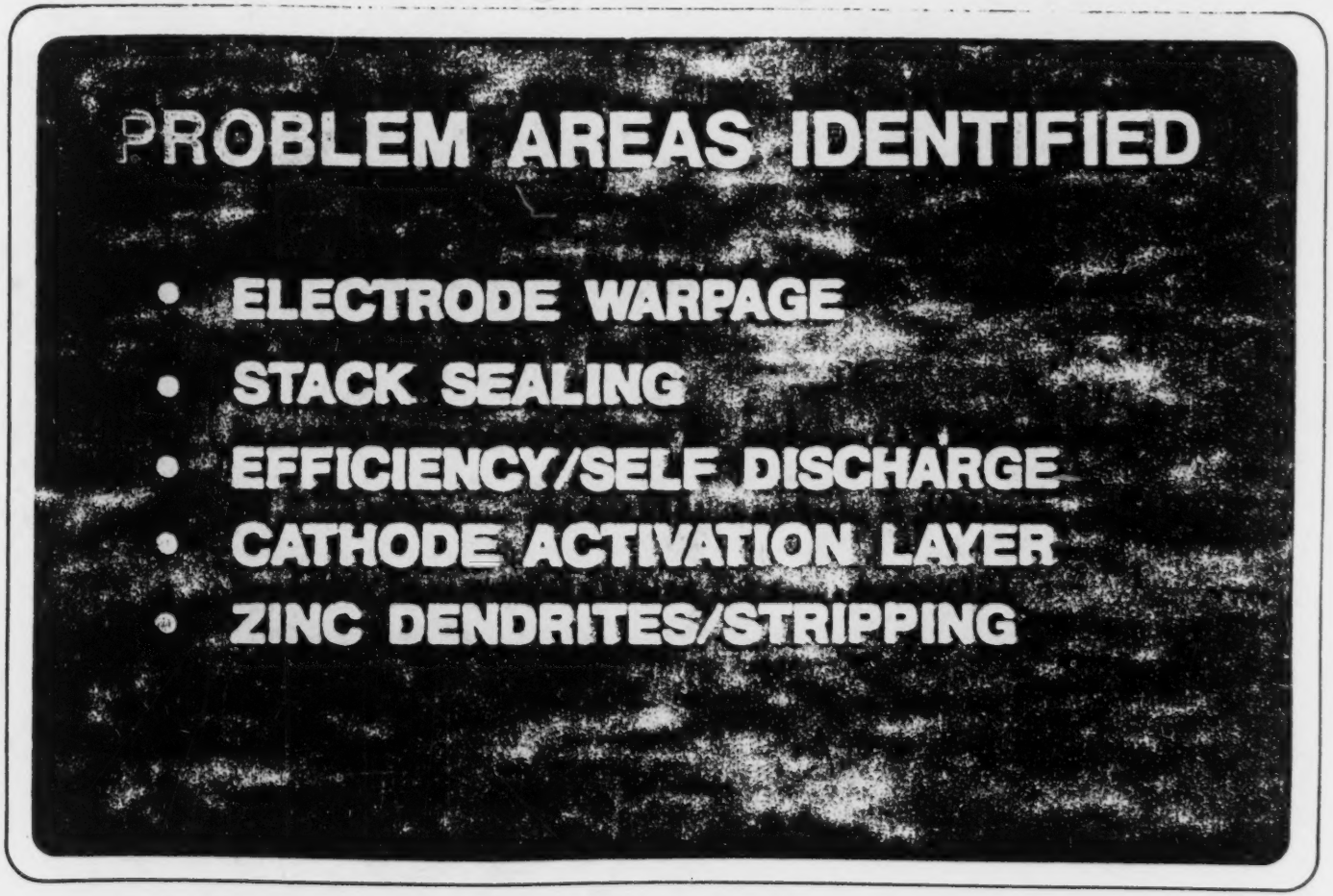

BATTERY PERFORMANCE GOALS*
FY 1990
Specific Energy
56 Wh/kg
Specific Power
79 W/kg
Life
450 cycles
Energy Efficiency
75%
Price (1985 Dollars)
$72/kWh
*Based on FUDS cycle

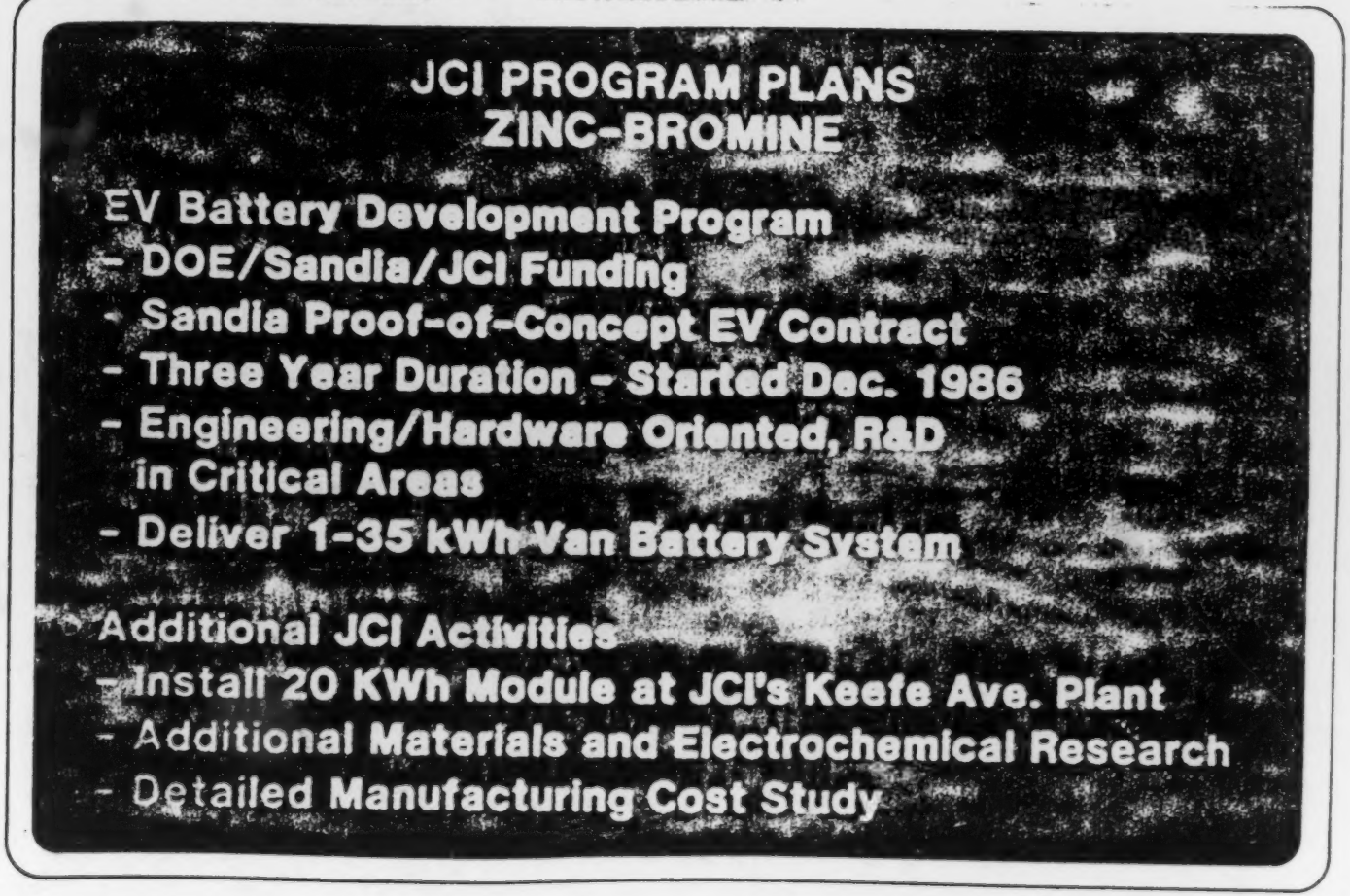

PROGRAM FUNDING REQUIREMENTS
• Three years of engineering and research efforts
• Average total funding level (including JCI cost share) of $1.0 million per year

ZINC - BROMINE


ElectricVan




PROBLEM AREAS IDENTIFIED
• ELECTRODE WARPAGE
• STACK SEALING
• EFFICIENCY/SELF DISCHARGE
• CATHODE ACTIVATION LAYER
• ZINC DENDRITES/STRIPPING


JCI PROGRAM PLANS
ZINC-BROMINE
EV Battery Development Program
- DOE/Sandia/JCI Funding
- Sandia Proof-of-Concept EV Contract
- Three Year Duration - Started Dec. 1986
- Engineering/Hardware Oriented, R&D in Critical Areas
- Deliver 1-35 kWh Van Battery System
Additional JCI Activities
- Install 20 KWh Module at JCI's Keefe Ave. Plant
- Additional Materials and Electrochemical Research
- Detailed Manufacturing Cost Study

ZINC-BROMINE EV BATTERY
PROGRAM GOALS
Consistent Life of 1,000 Cycles
Energy Efficiency of 70%
Specific Energy 70 Watt-Hours per Kilogram
Specific Power at 120 Watts per Kilogram
35 kWh Nominal EV Battery Design
Manufacturable Cost of Less Than
$55 per Kilowatt Hour

PROGRAM FUNDING REQUIREMENTS

- Three to Four Years of Engineering and Research Efforts
- Average Total Funding Level (Including JCI Cost Share) of $1.2–$1.4 Million per Year

Mr. HAYES. Dr. Halsall, while they're making that change, the comment made toward the end, the continuity being required, does that suggest that your work would stop if the DOE funding were to be terminated?

Dr. HALSALL. We, over the last two or three years in the advanced lead acid effort, in particular, we went from a significant funding level on the order of $5 to $6 hundred thousand a year, down to a level of less than $200,000, and the effort on our early approaches to flow-through would have been discontinued, had the last—the 1986 contract not been forthcoming.

We cannot see an application for that in our existing businesses, and therefore we would not be independently supporting it. We do, however, feel that with a potential of better than 60 percent improvement in active material usage, it's a very strong plus in the technology, and it needs to be applied.

But the packaging of today's automotive batteries and the advanced systems and the super-lightweight structures, as the industry moves forward with the existing ICEs, would not permit it's use in there. It wouldn't be cost-effective.

Mr. HAYES. There's only one other thing. What's a range comparison with lead acid and zinc bromine?

Dr. HALSALL. Well, we are projecting that the zinc bromine will probably be about 30 to 50 percent better than the lead acid. But the key here is that because the potential of the zinc bromine system is a somewhat lower weight system, because the electrodes themselves are polypropylene with filled polypropylene inner materials, it's almost an all-plastic stack. The big block you saw, the high-voltage stack, is virtually a series of vibration-welded polypropylene laminates. Each of those weighs less than a third of a pound. An equivalent lead acid unit, each one weighs in excess of 7/10ths of a pound, even with the plastic integration in the combo program.

So the thing is that you could increase the range by more than 50 percent on a volume base, and if you wanted to equal on a weight basis, you could probably get close to a doubling.

The strongest of the pluses, I think, to the zinc bromine packet is this business of ambient temperature operation, because advanced systems—and we love to look at things like sodium sulfur also, because we're a manufacturer—but the sensitivity in having to hold systems at 400 degrees or, you know—these tricky ends add considerably to the final cost complexity of the package.

Mr. HAYES. Thank you very much.

I'm sorry, Mr. Strang. Please excuse me for holding you up.

Mr. STRANG. No, that's fine. Thank you.

I guess as we get this focused, I should say that you introduced me originally as Dr. Strang, and I want to correct that for the record.

Mr. HAYES. Oh, did I? I'm sorry. I guess I was looking at Dr. Halsall.

Mr. STRANG. I appreciate that, but since it's on the record.

I'm from the AiResearch Manufacturing Company. As shown here, we're another part of the Garrett Corporation, just like our turbine engine company is, and I just want to put that in perspective.

The next four Vu-graphs are going to be right out of our testimony. They're in the back of it. I think we can get through this quite easily.

What I'm going to talk about is something called the monolithic solid oxide fuel cell. Now this device is a solid-state device, and it offers advances over liquid fuel cells, much like the transistor did over the vacuum tube. It's that level of technology advancement.

It operates at 1800 degrees. That's the operating temperature where the chemical reaction takes place most efficiently, and it can do that because it's a ceramic unit. [See footnote 3 in appendix.] It has multi-fuel capability, as proven by tests at Argonne National Labs—hydrogen, a lower molecular weight; hydrocarbons like natural gas, methane, ethane.

It's very lightweight and compact. It looks on the right like a corrugated box. That's about a nine-inch cube, and those little corrugations are the prime surface. [See footnote 4 and 5 in appendix.] They're packed in quite tight, much like the radiator in your car. There's no supporting structure. It's all prime surface that does useful work.

It has very high power per unit volume, and I'll get into that a little later.

What are the benefits? Well, it's very highly efficient, efficiencies in excess of 60 percent. It is very clean-burning, and as all fuel cells are, it's quiet. It's lightweight and small, and it may have application for transportation. Some of the other applications, we'll talk about also.

And it's potentially a very low-cost unit, because it's made out of ceramics. They're abundant. [See footnote 6 in appendix.]

It's performance comparison, the specific power, you can see, beats all the others by a long way. The chart there shows it very graphically, but to illustrate it, some of the predictions for the size of this unit, if we had about a cubic foot of this monolithic solid oxide fuel cell here, it would produce about 100 kW when fully developed. So the potential is really there, but it is far out.

And when it is fully developed, we see many applications, and we've been around talking to a lot of people in the Government, as well as private industry—in power production, transportation, both ground and air, SDI applications, and, as you can see, the potential is unlimited.

And that completes my testimony. I got you out of here before Chairman McCurdy returned. [Laughter.]

[The prepared statement of Mr. Strang follows:]

THE GARRETT CORPORATION TESTIMONY

PREPARED FOR

THE HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
SUBCOMMITTEE ON TRANSPORTATION, AVIATION, AND MATERIALS

HEARING
ON FY88 BUDGET
FOR THE DEPARTMENT OF ENERGY
TRANSPORTATION PROGRAMS

MARCH 3, 1987

JAMES STRANG
DIRECTOR OF ENGINEERING
ENVIRONMENTAL AND HEAT TRANSFER SYSTEMS ENTERPRISE

AIRESEARCH MANUFACTURING COMPANY
A DIVISION OF THE GARRETT CORPORATION

JAMES E. STRANG
Director of Engineering
Environmental and Heat Transfer Systems Enterprise

Education

B.S. in Mechanical Engineering, University of California at Berkeley, 1965.

M.S. in Mechanical Engineering, University of California at Berkeley, 1966.

Work History

1966 to date: AiResearch Manufacturing Company

- Director of Engineering, Environmental and Heat Transfer Systems Enterprise
- Chief Engineer, Environmental and Energy Systems
- Program Manager, Aircraft Systems
- Senior Project Engineer, Environmental and Energy Systems
- Project Engineer, Environmental and Energy Systems
- Assistant Project Engineer, Environmental and Energy Systems
- Senior Development Engineer, Environmental and Energy Systems
- Development Engineer, Aerospace Systems
- Preliminary Design Engineer, Preliminary Design

Responsibility/Experience

Mr. Strange has been Director of Engineering, Environmental and Heat Transfer Systems Enterprise since 1985. As Director of Engineering, Mr. Strang is responsible for all engineering and laboratory functions for environmental control systems, heat transfer and cryogenic systems and turbomachinery.

As Program Manager, Mr. Strang was responsible for managing all company activities for new applications and developmental tasks for a major aircraft program.

Mr. Strang's prior experience also includes work in various capacities of engineering on commercial aircraft environmental control systems, F-18 air conditioning systems, and Brayton-powered Rankine commercial space conditioning systems.

The following testimony is provided in support of funding development work on the monolithic solid oxide fuel cell (MSOFC). The work can and should be funded in the Fossil Energy portion of the Department of Energy budget. We believe that $2M in FY88 fund will be sufficient to begin the critical work described in detail below.

1. WHAT IS THE MONOLITHIC SOLID OXIDE FUEL CELL?

A fuel cell is a device that generates electricity by combining a gaseous fuel (hydrogen, hydrocarbon) with oxygen (from the air). The basic principle is similar to that of a battery. However, unlike a battery, a fuel cell does not run down or require charging. A fuel cell operates as long as both fuel and oxygen are supplied to the cell. The MSOFC is a unique and innovative design concept in fuel cell technology. The design employs thin ceramic layer components to form a compact, lightweight solid state structure. The MSOFC is composed of very small cells (1 to 2 mm in diameter) bonded into a single structure much like a block of corrugated paperboard (Figure 1). The walls of the corrugations are formed from thin (25 to 100 micrometers) ceramic layers of fuel cell components. Fuel and oxygen gases are conducted through alternating passages in the structure. The monolithic design results in a highly efficient and compact fuel cell power system unsurpassed by any existing technology.

2. WHAT ARE THE ADVANTAGES OF THE MONOLITHIC SOLID OXIDE FUEL CELL?

The monolithic solid oxide fuel cell has many attractive features:

- The primary feature of the MSOFC is its high efficiency. Because of the small cell size and thin components, the MSOFC achieves up to 60% efficiency. This efficiency is substantially higher than that of other energy conversion systems (for example, diesel engines) which typically have efficiencies of 35% or less. The MSOFC is also 10% more efficient than conventional fuel cells.

- The MSOFC is an inexpensive compact solid state device. No precious or strategic materials are used in the fuel cell. The components of the MSOFC are all thin ceramic layers and no additional structural support is required. (In the monolithic design, the thin ceramic layers are self supporting. In conventional fuel cells, thicker components and structural supports are needed).

- The MSOFC has an unequaled power per unit mass or volume (Figure 2). Thus, for example, a typical 100 horse-power diesel engine weighs about 800 pounds. A MSOFC system that produces the same power would weigh about 160 pounds. For transportation applications, the potential gain in vehicle performance is compounded by the fact that the weight of the vehicle's structural components can also be significantly decreased.

- The MSOFC, while operates at 1000°C (1,830°F), has multifuel capability. Suitable fuels include gasoline, alcohol, natural gas, synthetic gas made from coal or plant matter, and a number of other possibilities. Thus, expensive external fuel reforming equipments are not necessary.

- The MSOFC has potential for low cost manufacturing. The fabrication of the monolithic structure requires only a single high temperature processing step. The MSOFC also has potential for low cost operation. The fuel cell does not contain any liquids and needs only minimum maintenance.

- Like other fuel cell systems, the MSOFC has the characteristics of clean, quiet, and simple operation. For transportation applications, the MSOFC can improve air quality due to lower pollutant emissions compared with conventional technologies.

3. WHAT ARE THE NATIONAL BENEFITS OF THE MONOLITHIC SOLID OXIDE FUEL CELL?

The MSOFC is a new concept that offers a breakthrough in electric power generation technology. It has compactness, efficiency, and power per unit mass unmatched by conventional electric power generators. The MSOFC has the long range potential to meet a variety of national energy needs. These include powering airplanes and automobiles and producing electricity more efficiently than today's electric power plants.

Successful development of the MSOFC has significant implications on energy consumption and energy cost in the U.S. The MSOFC offers the potential for conserving fossil fuels, be it for electric utility power generation or for transportation. The use of the MSOFC reduces the amount of fossil energy required to produce a specific amount of electricity. Reducing the required energy inputs decreases the need for energy imports and also the amount of domestic GNP required for new energy production or utilization. These advantages, in turn, improve the balance of payments and free resources for other uses.

Environmental compatibility is another projected national benefit from the MSOFC. The MSOFC, like other fuel cell systems, is environmentally highly acceptable. Acid emissions and resulting air pollution are reduced by several orders of magnitude compared with conventional fossil-fuel-fired generators.

4. ARE GOVERNMENT AGENCIES AND INDUSTRY INTERESTED?

The MSOFC should be of interest to the U.S. government and private industry:

- The Department of Energy and its predecessor, Energy Research and Development Administration, have been involved in fuel cell research for more than twenty years. Currently, the department is supporting technology development of a number of conventional fuel cell systems. The MSOFC with its potential high efficiency and low cost should be an alternative fuel cell technology of interest to the department.

- The Department of Defense has an active interest in the application of fuel cell technology. The Air Force, Army, and Navy have been considering fuel cell as a power source for mobile and stationary energy requirements. The MSOFC with its high power and energy per unit mass is excellent as a lightweight power source for critical weapons and military installations. The Defense Advanced Research Projects Agency has funded the initial feasibility study of the MSOFC at Argonne National Laboratory.

- The National Aeronautics and Space Administration has developed fuel cells for space missions. The MSOFC, which has low weight, reliability, and high power capability, should be ideal for this type of application.

- The U.S. gas utilities are interested in on site fuel cell power plants for cogeneration and commercial applications. The use of the MSOFC could lead to lower cost on-site power plants because of simplified system requirements, more economical cell configurations, and high performance. Gas Research Institute has awarded a 20-month contract to the Garrett Corporation, with subcontracts to Combustion Engineering and Argonne National Laboratory, to examine the manufacturability of the MSOFC.

- The U.S. electric utilities have been supporting the development of fuel cell power plants for base-load and dispersed electric utility systems. For electric utility power generation, a system based on the MSOFC is expected to have the highest efficiency for utilization of fossil energy. Electric Power Research Institute has expressed some interest in the MSOFC.

- The automotive industries should be interested in the MSOFC for automotove propulsion because the fuel cell is so lightweight and has the desirable characteristics of high power/weight (required for startup, acceleration) and energy/weight (required for range) ratios.

5. WHAT IS THE STATUS OF THE MONOLITHIC SOLID OXIDE FUEL CELL?

The feasibility of the monolithic design has been demonstrated on a laboratory scale at Argonne National Laboratory. Single cells have been operated. Corrugated cell structures having prototypical dimensions have been fabricated using existing technology (Figure 3). The corrugated cells exceeded life and performance goals (Figure 4). However, there are several critical issues (concerning materials, fabrication methodology, and design) to be resolved, and several years of further research and development are needed to make the MSOFC practical.

The Garrett Corporation has identified the MSOFC as a potential future energy system and has formed a team with Combustion Engineering and Argonne National Laboratory to evolve this technology from its current status to a commercially viable product. The team provides the wide range of discipline and expertise required for such an effort.

- The Garrett Corporation has extensive experience in ceramic fabrication, system design, and components technologies. The Garrett Corporation has been developing compact ceramic heat exchangers; this technology emphasizes the intricate manufacturing of ceramic components for operation at high temperature. The experience in ceramic heat exchangers provides a solid base for the advanced fabrication and developments required for the MSOFC. The Garrett Corporation has experience in designing and building energy systems utilizing the interdisciplinary skills of heat transfer, turbomachinery, power conditioning, and control systems. Many subsystems and components for a fuel cell system are existing Garrett technologies (thus requiring no further development).

- Combustion Engineering is a leading company in providing equipments, products, and services for use in producing and processing energy. Combustion Engineering has extensive experience in design, construction, and market analysis of several energy systems including batteries, fuel cell power systems, and steam reforming systems

- Argonne National Laboratory is one of the nation's largest centers of research and related scientific studies. Argonne maintains close ties with industry to expedite the transition of new developments from the laboratory to the commercial stage. Argonne has pioneered the MSOFC technology including design, electrochemistry, and materials development. As a team member, Argonne will bring a wealth of scientific information useful for the development effort,

The development effort by the Garrett/Combustion Engineering/ Argonne team has been supported by substantial internal funding (Garrett and Combustion Engineering) and by Gas Research Institute.

There is no funding for the MSOFC from the fuel cell program (Fossil Energy) of the Department of Energy. To bring the MSOFC toward successful commercialization will require coordinated efforts of government, industry, utilities, universities, and national laboratories. Achieving this goal will provide the U.S. with a valuable product for internal use and for export. The potential benefits of the MSOFC are quite large and development of this key technology merits U.S. government support.

6. WHAT IS THE PLANNING FOR THE MONOLITHIC SOLID OXIDE FUEL CELL PROGRAM?

The objective of the program is to reduce the technical risk through the development of a technology base so that commercial MSOFC systems with high efficiencies, reasonable lifetimes, acceptable environmental impacts, and competitive costs are feasible.

The program will provide the basic technology that will complement the development work funded by Gas Research Institute and establish the MSOFC's performance, endurance, and manufacturability. Thus, in the first year, the program will be focused on developing a fundamental understanding of reactions, processes, and phenomena involved in materials processing and in an operating MSOFC. The scientific understanding should lead to improved

performance, increased performance life, and increased cost effectiveness of the fuel cell. The first year research also provides the direction for future technology development. In future years, further basic research into identified issues such as materials, fabrication methodology, and design will create a technology base that will be used to extend the MSOFC development from proof of concept toward practical applications.

7. WHAT DO WE RECOMMEND?

- Continue funding the present Department of Energy fuel cell program.
- Initiate funding for the monolithic solid oxide fuel cell in FY88.
- Fund $2M for the research and development of the monolithic solid oxide fuel cell in the FY88 fuel cell program of the Fossil Energy portion of the Department of Energy budget. The research and development will focus on fundamental studies of materials and critical phenomena in fabricating and designing the monolithic solid oxide fuel cell.

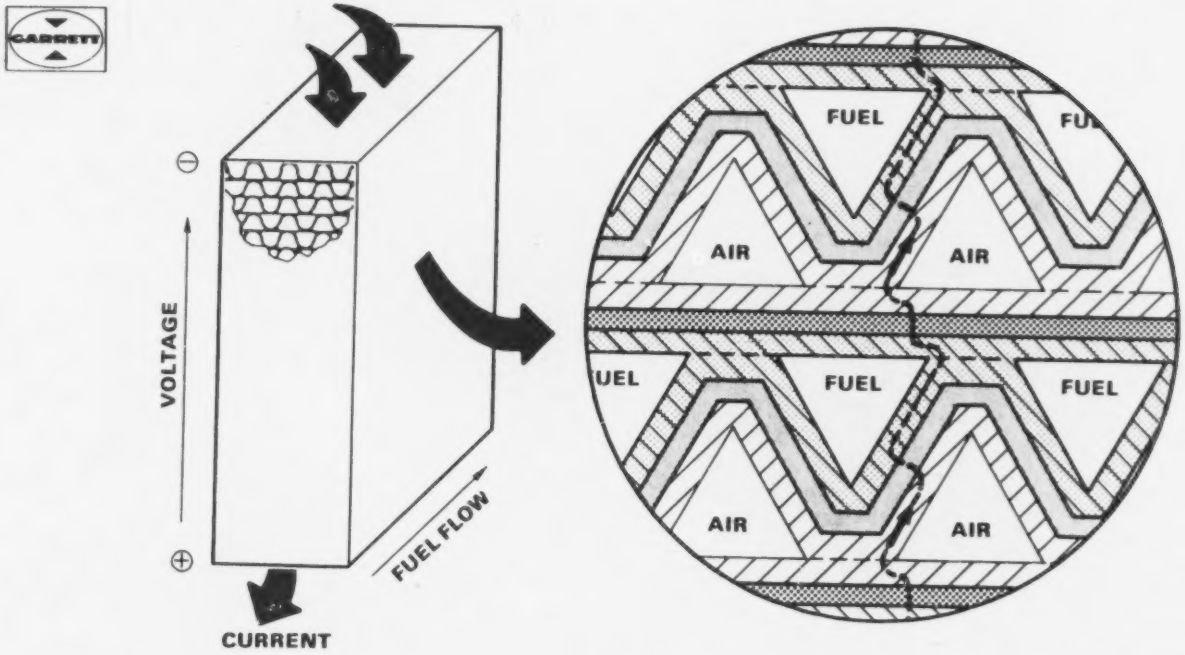


FIGURE 1 MONOLITHIC SOLID OXIDE FUEL CELL

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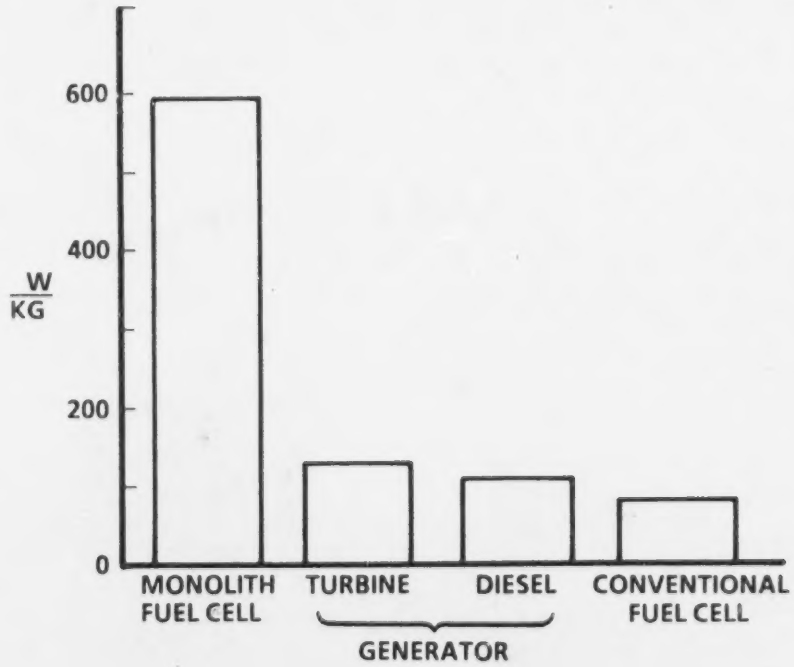

FIGURE 2 COMPARISON OF POWER PER UNIT MASS BETWEEN MONOLITHIC SOLID OXIDE FUEL CELL AND OTHER ENERGY SYSTEMS

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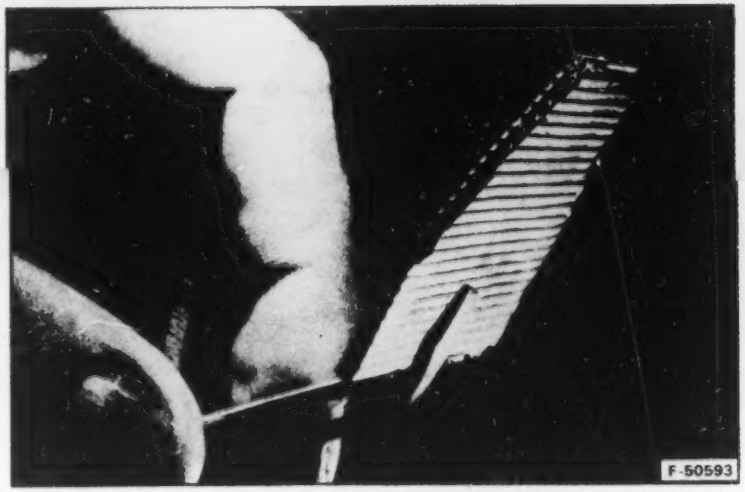

FIGURE 3 MONOLITHIC SOLID OXIDE FUEL CELL ARRAY

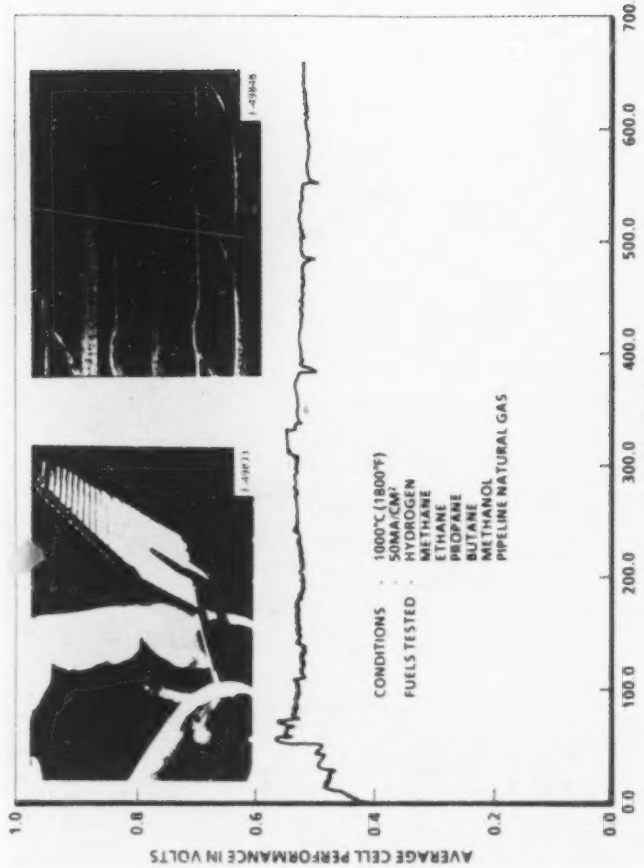

FIGURE 4 MONOLITHIC SOLID OXIDE FUEL CELL PERFORMANCE

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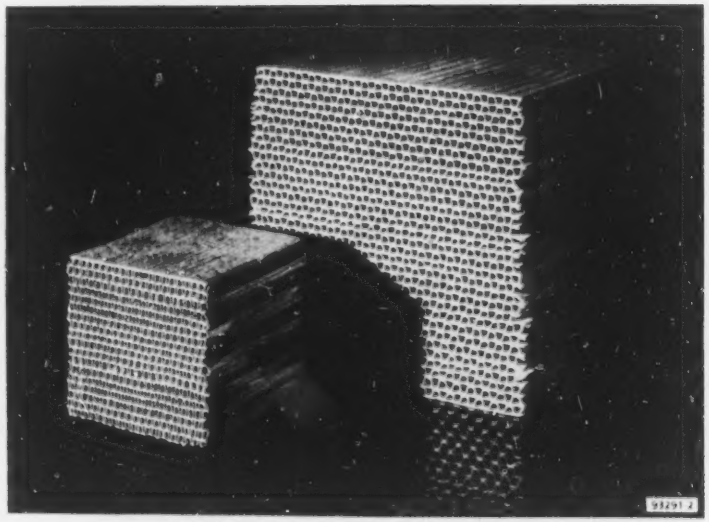
PRESENTATION MATERIALS

MONOLITHIC SOLID OXIDE FUEL CELL FOR POWER GENERATION

- SOLID-STATE DEVICE
- OPERATES AT 1800°F
- MULTI-FUEL CAPABILITY
- LIGHT WEIGHT/COMPACT
- HIGH POWER PER UNIT VOLUME



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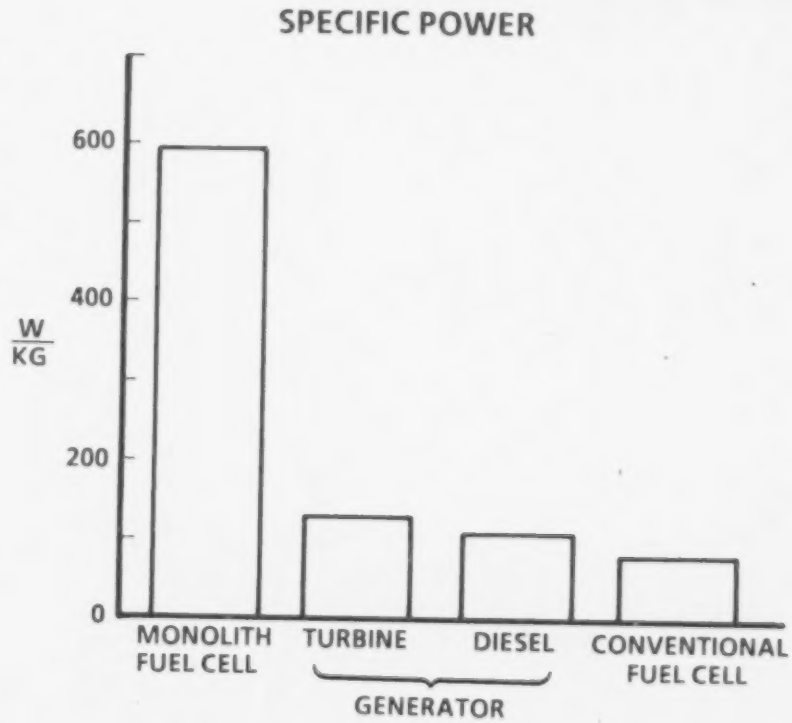
BENEFITS OF MONOLITHIC SOLID OXIDE FUEL CELLS

- HIGH EFFICIENCY
- POSITIVE ENVIRONMENTAL IMPACT
- LIGHT WEIGHT, SMALL SIZE, AND HIGH POWER SUITABLE FOR TRANSPORTATION APPLICATIONS
- POTENTIAL LOW COST DEVICE

PERFORMANCE COMPARISON



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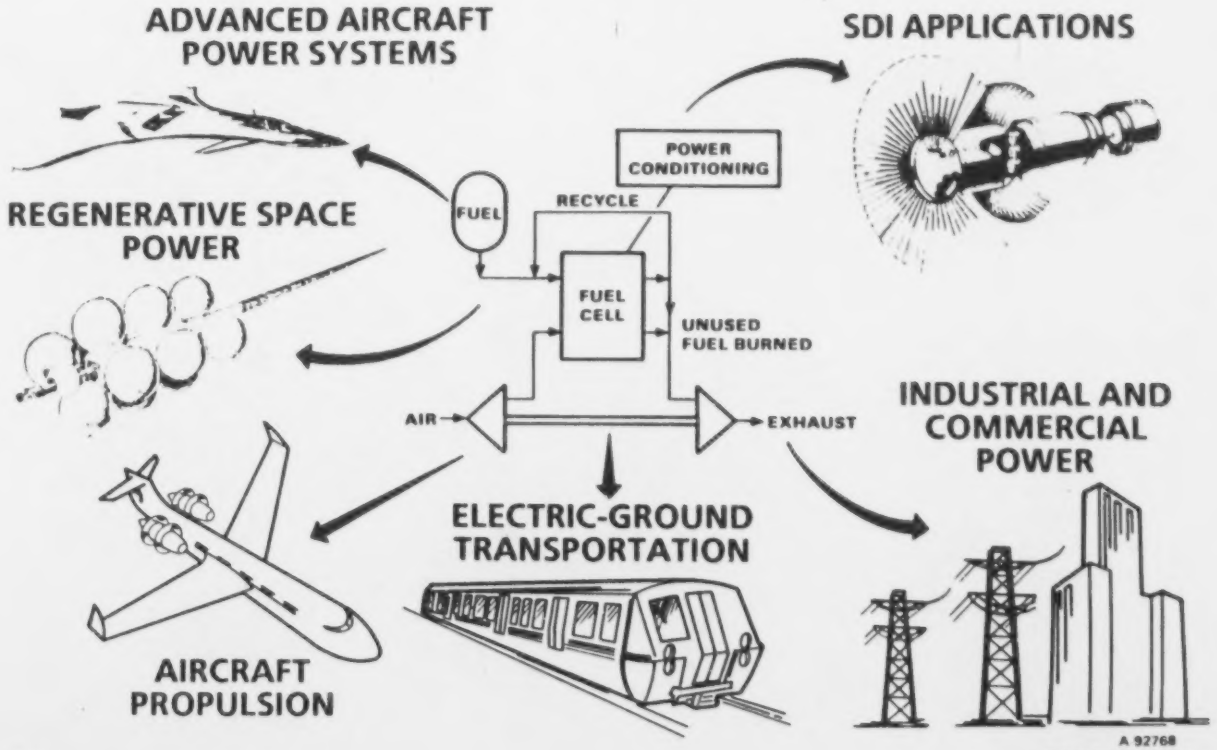
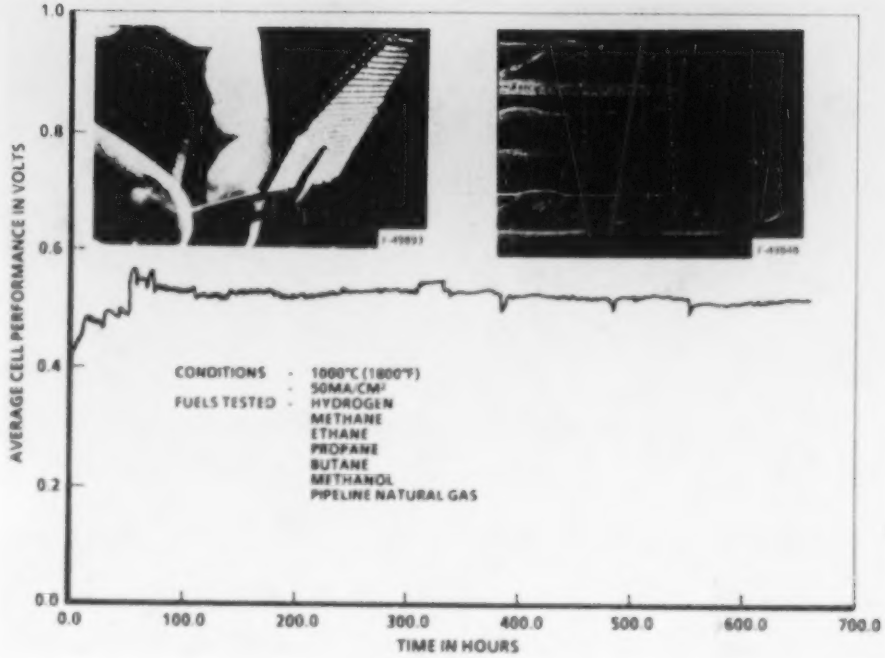
APPLICATIONS



Allied Signal Technologies

GARRETT

MSOFC MULTI-CELL TEST
AT ARGONNE NATIONAL LABORATORY



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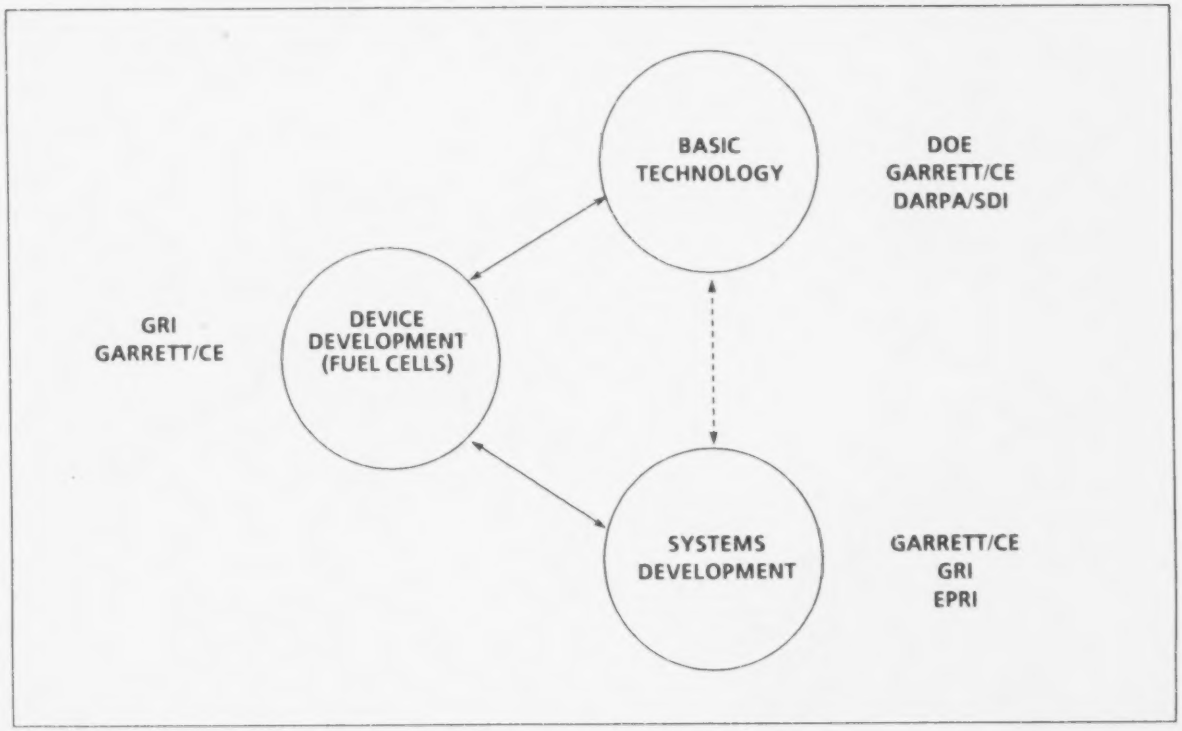
DEVELOPMENT TEAM

AIRESEARCH MANUFACTURING COMPANY
- CERAMIC FABRICATION
- SYSTEMS
- SUPPORTING COMPONENTS

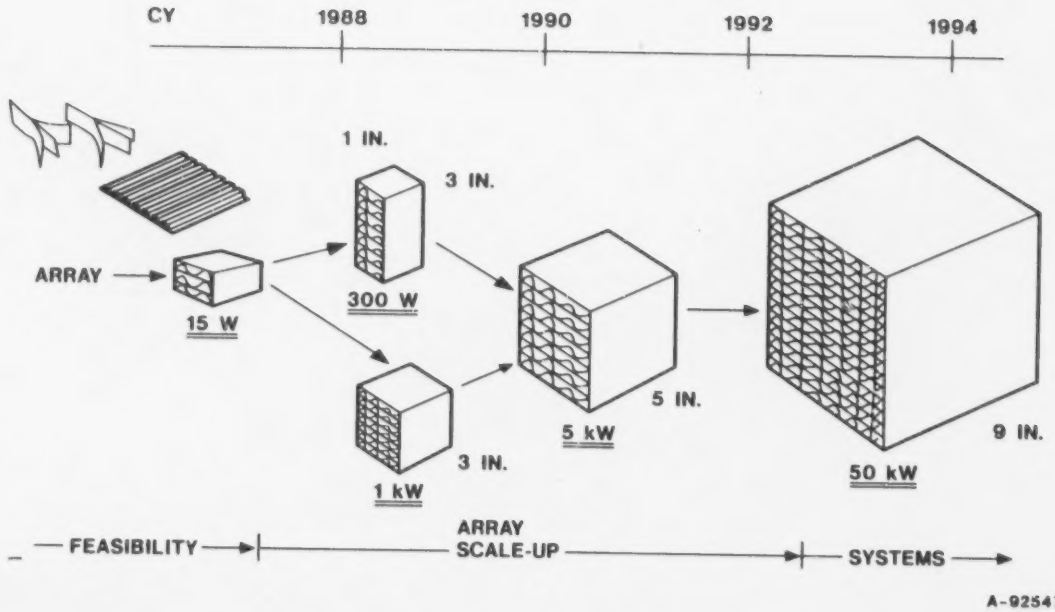
ARGONNE NATIONAL LABORATORY • UNIVERSITY OF CHICAGO •
- CELL TECHNOLOGY
- MATERIALS

COMBUSTION ENGINEERING
- INDUSTRIAL APPLICATIONS
- TESTING

ELEMENTS OF MSOFC DEVELOPMENT

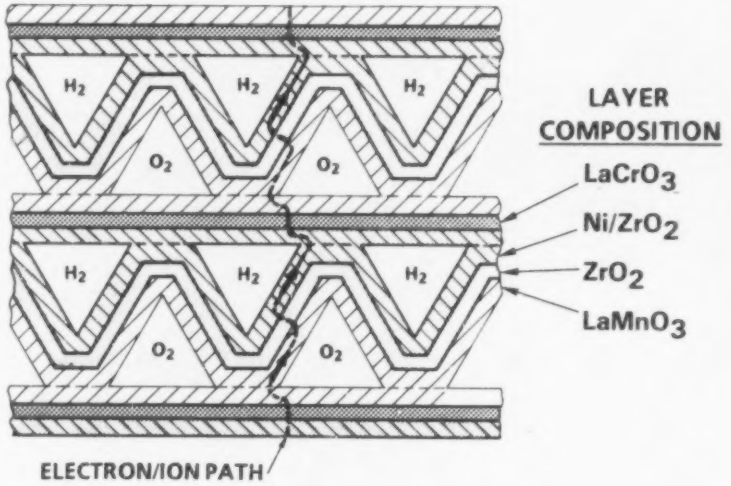


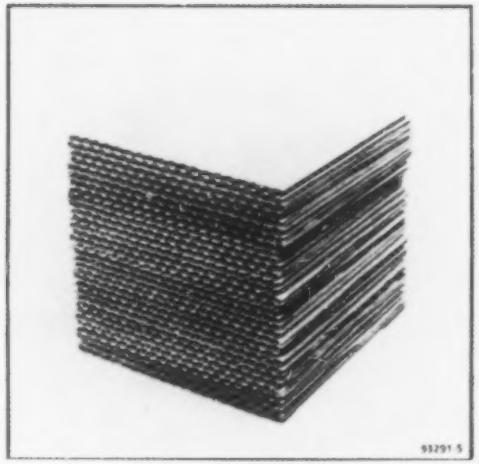
DEVICE DEVELOPMENT PLAN



AIRESEARCH MANUFACTURING COMPANY

MSOFC DETAILED DESIGN





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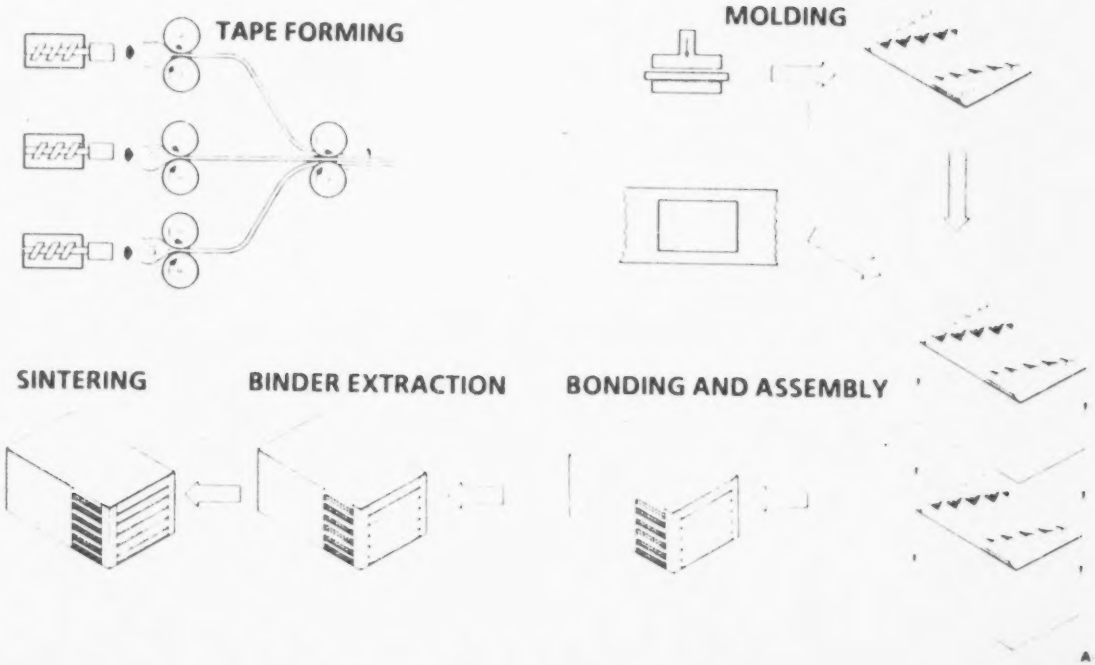

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Mr. HAYES. On the last of the portion of the presentation with the last graphic, you made a reference to SDI.

Has there been any relationship with DOD on funding or alternate funding?

Mr. STRANG. We have none right now. We've talked about it because of the potential for very high power in a small unit. But we've just made proposals so far.

This technology is ten years away. It's not here right now, and we're not trying to say it is. But it's worth developing.

Mr. HAYES. It's fascinating to me. I wish that I were more conversant to be able to ask better questions, and rather than hold everyone else here up, I might on some occasion corner you to give me a slow learning process to get me to the point where I can probably follow you more quickly and comfortably and ask additional questions.

But what about the electrical vehicle program? Have you been in touch with DOE on some kind of involvement with their activities?

Mr. STRANG. We've been mainly talking to the people at Fossil Energy, because of the potential for just energy improvement. And we want to do the basic technology work first, and the fabrication of the electro-chemical parts of the ceramics are quite important. It's a basic ceramic technology program to begin with, although Argonne has demonstrated that it will work, and we are teaming up with both Argonne and Combustion Engineering to form a development team now.

So we're serious about it.

Mr. HAYES. What's the key area to make it feasible, the key technical area? Is it the ceramics, or is it focused elsewhere?

Mr. STRANG. No. It's in the ceramic fabrication. Those little corrugations they use are actually three different elements fabricated into one thin strip, and it's an electrolyte, an anode, and a cathode, and it does the electrical/chemical process in a very, very thin piece of tape. And they're all different elements; they're all different ceramics.

We have, as part of the Allied Corporation, we have a very strong analytical group in our Allied basic chemical research, the Corporate Research Center, that are helping us with some of this very basic work with ceramics. But it has to have the right electrical/chemical processes, as well as the same coefficients of expansion, as you might imagine, how this thing heats up to 1800 degrees. So it's a basic ceramic technology.

Mr. HAYES. Thank you very much. I appreciate those of us who have gathered this afternoon, and I'm sure Mr. McCurdy will not be too disappointed, I think, in the last few minutes. We've certainly missed him, and, of course, I expect all of us to send flowers. [Laughter.]

Thank you very much.

Mr. STRANG. Thank you.

Mr. HAYES. And with that option, we'll conclude the subcommittee hearing.

[Whereupon, at 4:52 p.m., the hearing was adjourned.]

APPENDIX I

CORRECTIONS AND CLARIFICATIONS TO THE RECORD

1. Miss FITZPATRICK. "Well, it now has some 517 million barrels in it, which is about a 90 or 100 day supply of our net imports."

2. Dr. HALSALL. "As a corporation of $2.7 billion, batteries are approximately 20 percent of our volume."

Mr. STRANG.

3. "The 1800 degree temperature is needed for the conduction of oxygen ions in the ceramic electrolyte."

4. "A nine inch cube would produce about 50 kw."

5. "All the surfaces exposed to the fuel and air are active, i.e., available as reaction sites where the electrochemical transformation of the fuel and air occurs, producing direct current power."

6. "The ceramic materials are not precious or strategic materials. The fuel cell also has potential for low cost manufacturing."

APPENDIX II

STATEMENT OF DEBORAH LYNN BLEVISS, EXECUTIVE DIRECTOR, INTERNATIONAL INSTITUTE FOR ENERGY CONSERVATION

International Institute for Energy Conservation

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Garrett Corporation
Former Dep. Asst. Sec. for Energy Conservation, U.S. Dept. of Energy
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V.P. for Research, Georgia Institute of Technology
Former Asst. Sec. for Conservation and Solar Energy, U.S. Dept. of Energy
Honorable **Paul E. Tsongas**
Foley, Hoag & Elliot

President

Robert L. Pratt

Executive Director

Deborah L. Bleviss

April 2, 1987

Curtis Stanford
House Subcommittee on Transportation
Aviation and Materials
Science and Technology Committee
2324 Rayburn House Office Building
Washington, D.C. 20515

Dear Mr. Stanford:

Enclosed is a copy of testimony I am submitting for the record, as requested, on federal research priorities for energy efficiency in the transportation sector. I hope the text is useful in the Subcommittee's deliberations.

Sincerely,

Deborah Lynn Bleviss

Deborah Lynn Bleviss
Executive Director

Enclosure.

TESTIMONY ON
FEDERAL RESEARCH PRIORITIES
IN TRANSPORTATION ENERGY EFFICIENCY

Submitted to

the Subcommittee on Transportation, Aviation, and Materials

of the

House of Representatives

by

Deborah Lynn Bleviss
Executive Director
International Institute for Energy Conservation

April 2, 1987

Mr. Chairman and Members of the Subcommittee, thank you for the opportunity to submit testimony on research priorities for the federal transportation conservation budget. My name is Deborah Bleviss and I am the Executive Director of the International Institute for Energy Conservation. My remarks will be drawn largely from a study I completed while Associate Director for Energy and Environment at the Federation of American Scientists on the future of fuel economy in light motor vehicles.1

While most of the those who have testified on the transportation budget have looked at the specific features proposed in the Administration's budget, I would like to take this opportunity to look more broadly and ask the following question: if the slate were wiped clean, what should federal research priorities be? It is appropriate at this point to summarize the key findings from my study:

- Another oil crisis is both inevitable and imminent. With OPEC members sitting on two-thirds of the world's remaining oil reserves, global dependence on OPEC will be increasing in the years ahead, as it already is. By the mid-1990s, OPEC will probably be in a similar position of dominance as we witnessed in the late 1970s when it was pumping oil at more than 90 percent of its capacity.

- Structural changes within the U.S. will render it less able to respond to a future oil crisis than it has in the

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1 Presently itled Preparing for the 1990s: The World Automotive Industry and Prospects for Future Fuel Economy Innovation in Light Vehicles, it will be published by Quorum Books at the beginning of 1988.

past. With easily recoverable domestic petroleum reserves dropping sharply, the option of increasing domestic production to help mitigate such a crisis is questionable. Predictions have been made by some that domestic production could be as low as 4 million barrels a day (MMBD) by the turn of the century.2 Moreover, the domestic automotive industry is anticipated to be retrenching in the face of severe competition, with perhaps as much as 35 percent of its capacity lying idle.3 Thus, its ability to retool to meet the demand for lower petroleum dependence will be significantly less than the late 1970s, when it enjoyed almost complete dominance of the North American market.

- The transportation sector will bear the brunt of the next crisis. Since the first oil crisis, U.S. oil use has become increasingly concentrated in the transportation sector, growing from 51 percent in 1973 to 63 percent in 1986.4 And almost 60 percent of the oil consumed in the transportation sector is by light vehicles (automobiles and light trucks).5 Furthermore, unlike other energy consuming sectors that can switch to non-petroleum-based fuels, the transportation sector has almost no fuel switching options.

- A future oil crisis would prove disastrous to the domestic light vehicle industry. As already noted, the industry is anticipated to be retrenching in the face of severe foreign competition. One area of retrenchment is anticipated to be in domestic small car production; U.S. automakers will probably eliminate most of their own production of these vehicles, instead becoming distributors of cars made by others. Should another crisis materialize, then, they will have little to fall back on to meet increased consumer demands for fuel economy. Further loss of market shares and possible bankruptcies for some could well result.

- Through the end of the century, the only option available for reducing the oil dependence of the transportation sector is to improve the efficieny of its fuel utilization. Alternative fuels are too infant in their development and face too many institutional barriers to expect any significant penetration in this time frame.

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2 Office of Technology Assessment, Oil and Gas Technologies for the Arctic and the Deepwater, May 1985.

3 Automotive News, 1/13/86.

4 DOE Monthly Data Report #32, September 1986.

5 Oak Ridge National Laboratory, Transportation Energy Data Book: Edition 8, ORNL-6205.

- The potential for significantly reducing the fuel consumption of light vehicles by raising their fuel economy is quite high. Technologies offering high efficiency are presently under development, many of which could be introduced into production before the turn of the century. Prototype vehicles have been put forward in Europe, Japan, and the U.S. that offer composite fuel economies in excess of 60 miles per gallon without sacrificing other consumer amenities such as safety, comfort, performance, and acceptable emissions.

- The U.S. light vehicle manufacturing industry, as a whole, lags far behind its competition, particularly the Japanese, in developing fuel efficient technologies. Early American leads in a given technology are rarely capitalized upon, and repeatedly American companies are "beaten" in bringing an efficient technology to the market.

- Outside of the U.S. light vehicle manufacturing industry, there is no lack of American innovation in light vehicle efficiency technologies. Many promising efficiency technologies are the brainchildren of American academic institutions, small research-oriented businesses, and numerous parts manufacturers, often fostered initially with support from the Departments of Energy and Transportation. However, these institutions have repeatedly found the interest of the light vehicle manufacturing industry in this country in their work to be minimal. As a result, promising American technologies have been shelved, or, worse yet, sold to overseas competitors.

Needless to say, these findings are quite worrisome. The spector of a country held hostage to OPEC and an auto industry in retreat is once again on the horizon. The important question, though, is whether the present research efforts of the federal transportation conservation program hold any hope for helping to ameliorate these anticipated problems.

Unfortunately, the answer appears to be almost none. Unlike the conservation programs in the other energy consuming sectors,

the transportation program has always been very long term in focus, with an eye on technologies applicable more for the next century rather than for the next decade. Furthermore, there has consistantly been a preoccupation within the transportation conservation program with "exotic" technologies at the expense of more common ones, even if the latter clearly have considerable conservation potential and are preferred by industry. Finally, there has been a consistant prejudice in favor of concentrating only on engine technologies even though significant energy loss also occurs beyond the engine and the potential for reducing such loss is quite high.

An examination on a case-by-case basis of the present research priorities of the federal program illustrates these problems. To begin with, considerable funding has been and is proposed to continue to be put into the development of a gas turbine engine that will enjoy a thirty percent efficiency improvement over today's conventional engines. At first glance, this appears a worthy goal. But, on reflection, nagging issues arise. The turbine is a totally different type of engine than used by today's vehicles. Are the efficiency improvements it offers, then, sufficient to justify the consumer resistance that will undoubtedly appear in reaction to its substitution for today's spark ignition (gasoline) and Otto-cycle (diesel) engines?

A quick survey of technologies under development cannot help but raise some major doubts. Borrowing on an idea originally proposed by General Motors, Toyota has already developed an ultra-lean-burn spark-ignition engine for its production Carina that has improved fuel economy as much as 20 percent over the conventional spark-ignition engine.6 Isuzu and Ford of Europe are selling light trucks with direct-injection (DI) diesel engines that enjoy 18 to 20 percent fuel economy improvements over their conventional indirect-injection (IDI) counterparts.78 And Isuzu has promised that by 1990 it will have a ceramic diesel engine in a production vehicle that will have a 30 percent improvement in fuel economy over its non-ceramic counterparts.9 If improvements of these magnitudes can be gained from conventional engines, why are we pursuing the development of a new engine?

Similarly, let us examine the support for electric vehicle research. Electric vehicles may well be a part of the future non-petroleum based motor vehicle fleet. But automakers and auto

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6 Matsushita, Souich, et. al., "Development of the Toyota Lean Combustion System", SAE Paper # 850044.

7 Takeuchi, Koichi, et. al., "The New Isuzu 2.5 Liter and 2.8 Liter 4-Cylinder Direct Injection Diesel Engine", SAE Paper #850261.

8 Bird, G.L. "The Ford 2.5 Litre High Speed Direct Injection Diesel Engine--Its Performance and Future Possibilities", SAE Paper # 85062.

9 Automotive News, 10/21/85.

analysts worldwide agree that until a major advance is made in battery storage capabilities, the range and speed contraints of such vehicles will necessarily limit their utilization. As a result, their penetration into the world's vehicle fleet in the years before the turn of the century will not be substantial nor, therefore, will their contribution to preventing, or at least containing, the ill-effects of the next oil crisis.

The same conclusion can be reached with regard to liquid alternative fuels, yet another area for federal support. In this case, the problem is not so much with the technology constraints as with the institutional barriers hindering the widespread use of these fuels. The producers of these fuels are reluctant to significantly increase their production or to invest in distribution centers until they are assured that light vehicle makers will manufacture vehicles geared to use these fuels. On the other hand, light vehicle makers are unwilling to commit to manufacture such vehicles until they are assured that adequate fuel supplies and distribution centers will be available.

Automakers and analysts agree that the only resolution to this problem is the substantial intervention of the government through subsidies and regulations, an unlikely occurance, at least in the short term. Thus, penetration of alternative liquid-fueled vehicles before the end of the the century can once again be expected to be minimal.

Yet another area of focus for federal support has been advanced materials development, which concentrates principally on ceramics development. There is no doubt that this is an important area of development. Ceramics is one of the most promising "new" technologies applicable to transport vehicles, as well as other energy uses. Moreover, the Japanese have a well-recognized lead on the U.S. in this arena, and therefore any assistance to overcome this gap is important.

But basic research in ceramics is simply not sufficient. The Japanese lead in ceramics development extends to its application as well. If ceramics are to be applied to an engine, major adaptations in engine design are required. The high temperature waste heat must be recovered, methods to improve efficiency at part-load operation--which accounts for a large fraction of a light vehicle's operation--need to be developed, and rapid combustion techniques must be employed. But, while DOE has supported ceramic engine prototype development for heavy-duty vehicles, no similar activity has occurred for light duty vehicles.

In fact, the one area where DOE funding priorities make sense because they are geared to address the problems coming along down the pike in the next decade is in its heavy-duty transport program. That program is one of applied research,

addressing actual engine-related designs, rather than just basic materials. And the focus of its technology work is short term enough to potentially have an impact on the coming crises of the 1990s. Yet, it also remains long term enough to be outside the purview of the current research efforts presently being supported by the private sector.

The irony of this well-defined research program, though, is that it will impact vehicles accounting for only just over 10 percent of the oil consumed by the transportation sector.10 Yet, there is no equivalent program for light vehicles--passenger cars and light duty trucks--which account for almost five times as much oil consumption.

The serious threats of the coming decade place an enormous responsibility on policymakers today. They can either choose to sit back, continue our present policies with perhaps some minor changes--such as funding one program a little more and another a little less--and hope these threats really do not materialize. Or they can seek to put in place now programs and policies that will address, and hopefully mitigate, those threats.

Taking the first path is quite dangerous, for the nation's national and economic security as well as the integrity of a major jobs-laden industry is at stake. Taking the second path is

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10 Oak Ridge, Op.Cit.

a much wiser course of action, but it also requires a lot of hard work as existing programs are substantially restructured. And among the programs that need such restructuring is the present transportation conservation program.

What should such a restructured research program look like? I would suggest the following guidelines in devising that program:

1. While some funds should remain to support research that can facilitate the transition to non-petroleum-based transportation fuels (e.g. electric vehicles, methanol), the bulk of attention in the federal program should be re-oriented to alleviating problems that are likely to occur before such a transition can take place. This means concentrating on fuel efficient technologies that can be brought to market by the turn of the century.

2. Priorities for such a research program should be based upon the following criteria: a) whether the technologies could be commercially feasible by the end of the century in time to help mitigate a future crisis; b) whether without federal support such technologies would largely be ignored by the domestic industry; c) whether the lack of any federal support would mean that overseas competitors would be likely to introduce the technologies first; and d) where there is foreign competition, whether there is sufficient lead time for federal support to make a significant difference in beating the competition to the market. With regard to the last point, it is worth noting that while the U.S. industry lags its counterparts in short, medium, and long term research, it is the longer term research where the gap is least pronounced basically because current efforts across the board are much weaker. Federal support for longer term efforts, then, could potentially be more effective in closing the technology gap.

3. The federal government neither cannot nor should not endeavor to conduct all the needed fuel economy research on its own. Such research is meaningless unless it can be adopted and commercialized by the domestic light vehicle industry. And this industry has a long history of ignoring research in which it does not have a vested interest. This means a cooperative research program is

critical. The present structure of the transportation research program--in which the industry co-funds the research costs--is a good place to start. But the industry must be as involved in the decisionmaking on what types of research to fund as it presently is in the research itself. By participating in the priority-setting process, automakers and their related supplier industries are more likely to feel the priorities make sense and therefore to want to take the research into commercialization.

4. The federal government must take an active role in encouraging the interaction between the domestic industry and the innovators in fuel economy technology so as to facilitate some "cross-fertilization". This could be accomplished through a variety of mechanisms. First, the innovators could be included with the industry in the decisionmaking in a federal cooperative research program. Second, the federal program could actively assist communication between the two parties, for example, by sponsoring fuel economy technology conferences similar to the one held in 1979 by the Department of Transportation. And finally, where federal funding is actually committed to the research of an innovator--which hopefully will occur whenever a technology is judged both promising and likely to go abroad if federal support is not offered--automaker representatives could be asked to sit on a review committee for the project.

5. The federal research program must be empowered with taking a technology far enough along to be assured it will be carried through to commercialization. The percentage of federal funding being contributed to this end might decline as the work becomes more advanced--with the industry supporting more of the costs--but a federal presence is required nevertheless. Simply supporting basic research and feasibility studies and then assuming the industry will step in if the technology is promising is both naive and wasteful of federal monies.

6. With regard to alternative fuels, care must be taken to focus the emphasis of the program on the major barriers to their utilization. Does it make sense to divert limited resources towards the design of electric vehicles when battery storage constraints will limit their utility, or should funds instead be concentrated on advanced battery research? Similarly, with alternative liquid fuels, does it make sense to allocate funds to technology research, when the principal problems are institutional?

What types of research might be funded by such a program? Attached to this testimony is a chart showing the promising efficiency technologies for light vehicles that could appear in the remaining years of this century, and when they would be most likely to do so. Among the "medium term" technologies--those that could reach commercialization in five to ten years--are the first generation of ceramic diesels (containing some ceramic components); "clean" versions of stratified charge, ultra-lean-burn, and direct injection diesel engines; the second generation of continuously variable transmissions or CVTs (with unlubricated belts and electronic controls); polymer body panels; composite chassis and engine parts; aluminum bodies; magnesium engine and load-bearing parts; electric power steering; and aerodynamic body styling.

And among the "longer term" technologies--those that could reach commercialization in ten to fifteen years--are solid engine lubricants, advanced ceramic "adiabatic" diesel engine with all ceramic parts, oxygen separating engines, beltless CVTs, solar-powered accessories, highly aerodynamic body styling, and engine storage systems.

Most of these technologies, if current trends continue, will likely see commercialization in the hands of competitors of the American light vehicle-making industry, leaving the domestic industry ill-prepared for a new crisis. A restructured federal

research program, however, could likely produce a different result.

In conclusion, then, I would strongly urge this subcommittee, before it begins the process of assigning priorities to the present Administration funding request, to step back and assess what its goals are for transportation conservation research. If they indeed are to limit the damage that might be caused by an increasing national dependence on unstable petroleum suppliers, then the current program simply cannot deliver. Instead, a massive restructuring of program priorities and procedures is required. This is certainly more time-consuming than continuing with the status quo, but the impact on the nation's well-being will most assuredly be more substantial.

ESTIMATED DATES OF PRODUCTION-READINESS
FOR ADVANCED LIGHT VEHICLE FUEL EFFICIENT TECHNOLOGIES

1990	1995	2000
[MATERIALS]		
Composite Body Panels	Polymer Body Panels	
Composite Load-Bearing Parts	Composite Chassis	
	Fiber-Reinforced Plastic Engine Parts	
Increased HSLA Steel Use		
Aluminum Load-Bearing Parts	Aluminum Body	
Fiber-Reinforced Aluminum Engine Parts		
Magnesium "Interior" Parts	Magnesium Engine, Load-Bearing Parts, And Wheels	
Ceramic Liners And Turbocharger Blades		
[AERODYNAMICS]		
	Drag Coefficients In The Middle ".20s"	Drag Coefficients In The Low ".20s"
[TIRES]		
New "Kinetic" Tire-Making Processes	"Plastic" Tires	
[ACCESSORIES]		
Variable Displacement Air Conditioner		Solar Power For Accessories
Advanced Electronically Controlled Air Conditioner		
Laminated Reflecting Film Auto Glass		
"Smart" Alternator	High Efficiency Alternator	
Variable Power Steering	Electric Power Steering	
Electroluminescent Lighting		
[STOP-START/ENERGY STORAGE]		
Engine Stop-Start With Flywheel Storage		Complete Energy Storage

ESTIMATED DATES OF PRODUCTION-READINESS
FOR ADVANCED LIGHT VEHICLE FUEL EFFICIENT TECHNOLOGIES

1990	1995	2000
[ENGINES]		
Variable Turbocharger	Torch Ignition	Solid Lubricants
Pressure Wave Supercharger	1st Generation Ceramic Diesel	Advanced Ceramic Diesel
Variable Valve Engine	Advanced Variable Engine Displacement	Oxygen Separating Engine
	Dual Circuit Cooling	
	Electronically Controlled Cooling	
	Peak Pressure Ignition Sensor	
Electronically Controlled IDI Diesel	"Clean" Stratified Charge "Clean" DI Diesel	
	"Clean" Ultra Lean Burn	
[TRANSMISSIONS]		
1st Generation All-Gear Lock-Up Clutch	2nd Generation All-Gear Lock-Up Clutch	
Electronically Controlled Automatic Transmission With Torque Converter		
	Electronically Controlled Automatic Transmission With Synchromesh Clutches	
Lubricated Belt CVT With Hydraulic Control	Electronically Controlled "Dry" Belt CVT	Beltless CVT